APPLICATION OF VARIABLE-RATE IRRIGATION TECHNOLOGY TO CONSERVE WATER AND IMPROVE CROP PRODUCTIVITY

by

Aghil Yari

A thesis submitted to McGill University in partial fulfillment of the requirements

of the degree of

Doctor of Philosophy

Department of Bioresource Engineering

Macdonald Campus of McGill University

Montreal, Canada

April, 2017

Abstract

Variable-rate irrigation (VRI) is an emerging technology to optimize water and energy consumption, increase crop yields, and minimize environmental impacts. VRI technology is capable of applying irrigation water spatially across a field to meet crop requirements on pre-defined management zones, taking spatial variability of soil properties and landscape features into account. The goals of this research project were to assess the performance of VRI, to investigate field spatial and temporal variability for delineating irrigation management zones, and to quantify the potential water and energy savings, and crop productivity benefits of VRI for two crop types in southern Alberta. The research included a four-year field experiment during the 2013 to 2016 growing seasons at the Alberta Irrigation Technology Centre (AITC) in southern Alberta, Canada. In the 2013 and 2014 growing seasons, the experimental site was seeded to Hard Red Spring (HRS) wheat, and during the 2015 and 2016 growing seasons, Russet Burbank potato was planted. In 2013 and 2014, the performance of a center pivot irrigation system (CPIS) retrofitted with a commercial VRI package was assessed. Overall, the uniformity of application both along the system's lateral and in the travel direction were above 90% for the majority of the trials under the different wind speeds and water application depths. Wind speeds greater than 3.3 m s^{-1} reduced application uniformity by 3.9%. The mean application uniformity increased by 5.7% along the pivot lateral under both constant and variable application depths with the updating of the sprinkler package during the 2014 growing season.

In addition, the volumetric flow measurement at the pivot point of the system indicated that up to 34% water savings can be achieved with VRI versus non-VRI. Moreover, the average energy cost decreased by 18% with VRI during the 2013 and 2014 seasons due to non-application of water to

areas such as ponds, roads, and non-cropped areas in the study site. In an effort to delineate irrigation management zones for VRI application, temporal and spatial variation of soil physical and chemical properties were assessed. A stepwise multivariate regression approach and a fuzzy C-mean clustering algorithm were used to identify optimum number of variables for management zone delineation. It was found that soil electrical conductivity (EC), pH, and field elevation were the best of 10 parameters for management zone delineation. The validity criteria identified that the three management zones were optimum for the study site using EC and field elevation. Statistical analyses showed that the delineated management zones were significantly different in terms of crop yields. In the 2014 growing season, the highest wheat yield (4.80 t ha^{-1}) was produced within the management zone three where the EC value was low and elevation was high. The lowest wheat yield (2.22 t ha^{-1}) was in the management zone one situated in the high EC and low elevation areas. The AquaCrop model was used to optimize crop productivity within the three management zones. Simulation of HRS wheat growth in the study area under the different irrigation scenarios indicated that the crop yield would be improved with optimum irrigation application and drainage management.

The study also has investigated the potato productivity under VRI technology in 2015 and 2016 growing seasons. Three irrigation applications (high, normal, and low irrigation treatments) were applied to Russet Burbank potatoes. In 2015, higher water application in the experimental plots resulted in no significant improvement to potato yield. The harvest of tubers in normal irrigation plots proved to be more uniform in quality and size of tubers. The high irrigation treatment had a higher marketable yield and the largest loss of deformed or small tubers. The average marketable yields in high, normal, and low irrigation treatments were 47.99, 46.25, and 41.81 t ha^{-1}, respectively. In 2016, there were no significant differences among irrigation treatments for any of

the yield and quality factors analyzed. This is likely because the differences in the amount of irrigation applied to the three treatments were very small due to precipitation over the growing season.

Key words: Variable-rate irrigation, crop productivity, management zones, water conservation, spatial and temporal variability, and center pivot irrigation system.

Résumé

L'irrigation à débit variable (IDV) est une technologie émergente qui optimise la consommation énergétique et en eau et augmente les rendements des cultures, tout en minimisant les impacts environnementaux. La technologie d'IDV peut distribuer l'eau selon les besoins spécifiques des cultures tels que déterminés selon des zones de gestion prédéfinies, prenant la variabilité spatiale des propriétés du sol et les caractéristiques du paysage en compte. Les objectifs de cette recherche étaient donc évaluer la performance de l'IDV, évaluer la variabilité spatiotemporelle des champs agricoles pour délimiter des zones de gestion d'irrigation, quantifier le potentiel en économie énergétique et en eau de l'IDV, et les avantages de la productivité des cultures de l'IDV pour deux types de cultures dans le sud de l'Alberta. Cette étude inclut une expérience sur le terrain d'une durée de quatre ans, entre les années 2013 et 2016, au Alberta Irrigation Technology Centre (Centre de technologie d'irrigation de l'Alberta) au sud de l'Alberta (Canada). Lors des saisons de croissance de 2013 et de 2014, le champ fut semé avec le blé de force roux de printemps (FRP), et, lors des saisons de croissance de 2015 et de 2016, la pomme de terre Russet Burbank. En 2013 et 2014, la performance d'un système d'irrigation à pivot central (SIPC) équipé d'un ajout commercial d'IDV furent évaluées. L'uniformité de l'application le long des axes latéraux et longitudinaux était supérieur à 90 % pour la majorité des essaies sous de différentes conditions de force du vent et de profondeur d'application de l'eau. Les vitesses de vent supérieures à 3,3 m s^{-1} ont réduit l'uniformité de l'application de 3,9%. L'uniformité moyenne de l'application a augmenté de 5,7% le long du pivot latéral à la fois avec des profondeurs d'application constantes et variables avec la mise à jour du paquet d'arrosage pendant la saison de croissance 2014.

De plus, les mesures du débit volumétrique au point de pivot du système indiquèrent que des économies en eau atteignant 34% peuvent être obtenues avec un système d'IDV, tandis que les coût énergétiques moyens diminuèrent de 18% par comparaison avec le système sans IDV lors des années 2013 et 2014 en raison de la non-application de l'eau dans des zones comme les étangs, les routes et les zones non cultivées sur le site de l'étude.

Les variations temporelles et spatiales des propriétés physiques et chimiques du sol furent mesurées afin de délimiter les zones de gestion d'irrigation pour l'IDV. Le nombre de variables optimal pour la délimitation fut identifié à l'aide d'une approche de régression multivariée et un algorithme de groupement des moyennes-C floues. Parmi 10 paramètres, la conductivité électrique (CE) du sol pH, et l'élévation du champ furent identifiées comme les meilleurs paramètres pour délimiter le champ en zones de gestion. Les critères de validité indiquèrent que les trois zones ainsi identifiées étaient effectivement les zones optimales pour le site d'étude utilisant CE et l'élévation du champ. Des analyses statistiques montrèrent que ces zones ont des différences significatives en rendement des cultures. Lors de la saison de croissance de 2014, le rendement du blé était le plus élevé (4,80 t ha^{-1}) dans les régions en zone de gestion numéro trois, là où là CE était basse et l'élévation plus élevée. Le rendement en grains le plus bas (2,22 t ha^{-1}) se trouvait dans les régions en zone de gestion numéro un, avec une CE élevé et une élévation inférieure. Le modèle AquaCrop fut utilisé pour optimiser la productivité des cultures dans les trois zones de gestion, utilisant des simulations de blé FRP sous de différents scénarios d'irrigation pour démontrer que le rendement des cultures pourrait être augmenté avec une application d'irrigation optimisée et gestion du drainage.

Cette étude évalua aussi la productivité des pommes de terre avec la technologie d'IDV en 2015 et en 2016. Trois régimes d'irrigations (haut, normal, et bas) furent appliqués aux cultures de pommes de terre Russet Burbank. En 2015, une application d'eau élevée dans les parcelles expérimentales n'a occasionné aucune amélioration significative dans les rendements de pomme de terre, et la récolte dans les parcelles témoins (irrigation normale) était plus uniforme en taille et en qualité des tubercules. Le traitement d'irrigation élevé a eu un rendement commercialisable plus élevé et aussi la plus grande perte de tubercules déformés ou petits. Le rendement moyen commercialisé dans les traitements d'irrigation élevés, normaux et bas était de 47,99, 46,25, et 41,81 t ha^{-1}, respectivement. En 2016, il n'y avait aucune différence significative entre les paramètres de rendement et de qualité analysés pour les différents traitements d'irrigation, probablement parce que les différences en irrigation appliquée aux trois traitements étaient minimes lors cette année dû à la précipitation élevée le long de la saison de croissance.

Mots clefs : L'irrigation à débit variable, productivité des cultures, zones de gestion, conservation de l'eau, variabilité spatiotemporelle, système d'irrigation à pivot central.

Dedicated to

My Beloved Parents and Wife

Acknowledgements

I am very fortunate to work with Professor Chandra A. Madramootoo. His support, advice, and encouragement for this research are greatly appreciated. The lessons I learned working with Professor Madramootoo have been invaluable to my work and life. I gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for the grant funding that facilitated this research project. I am grateful to the project partners, Alberta Agriculture and Forestry, Alberta Irrigation Technology Center, Sunrise AG Company for providing equipment and extensive in-kind support. There have been many people and partners along the way whom I would like to thank. One of those is Dr. Shelley A. Woods, scientist of the Alberta Agriculture and Forestry; her support and assistance in different aspects associated with my project were significant. I am also grateful to Brent Paterson and Rod Bennett director of Irrigation Management Branch, and Jim Parker, Brian Cook, and Mike Ellefson for their technical support in Alberta Agricultural and Forestry. I am also grateful to Ki Au, Gyan Mankee, and Mark Kadijk the members of Water and Soil Laboratory for their assistance with soil analyses during the four growing seasons.

I wish to thank my PhD Committee members; Dr. Viacheslav I. Adamchuk, Dr. Vijaya Ragavhan, Dr. Armando Jardim, Dr. Valérie Orsat, Dr. Shiv Prasher, Caroline Begg, and Dr. Zhiming Qi from the Department of Bioresource Engineering, McGill University, and Dr. Shelley A. Woods from the Alberta Agriculture and Forestry, and Dr. Rajiv Khosla from the Colorado State University.

Special thanks would be given to my friends and colleagues: Dr. Nader Foroud, Dr. Jala Jebellie, Dr. Barry Olson, Dr. Ravinder Pannu, Dr. Abdullah Darzi, Dr. Yasin Osroosh, Dr. Jamshid Rahimi, Dr. Maryam Kargar, Ferial Karimian, Ebi Nourozi, Faezeh Eslamian, Shima Keisandokht, Edris Madadian, Mahsa Ghasri, Paiya Darvishzadeh, Mohammad Javad Pouraghniaei, Mohsen Pourabedian, Farzad Saadatian, Divya Gupta, Naresh Gaj, Aidan De Sena, Bhesram Singh, Geneviève Grenon, Kaitlin Lloyd, Mfon Essien, Naeem Abbasi, Dr. Felix Jaria, Dr. Olanike Oladenola, Dr. Felexce Ngwa, Dr. Candice Young, Angela Grant, Dr. Ajay Singh, Dr. Alaba Boluwade, Laura Gilbert, Hsin-Hui Huang, Adele Harding, Beth Rice, Hofer Bonnie, Julien Malard, Mohammad Valipour, and Abhishek Kumar for their helps and supports. I would like in particular to express my appreciation to George Themelis and Kenton Ollivierre for technical support and Wendy Ouellette and Susan Gregus for their professional secretary assistance throughout the duration of my study.

My heartfelt thanks to my beloved wife, Zahra, who stood by me as motivator and encourager throughout the duration of my studies in my home county and Canada for almost 10 years. I take this opportunity to express my heartfelt thanks to my lovely son, Arvin, who was born in the middle of my PhD program and created happiness and joy in my PhD life. In addition, I would like to thank my siblings for their endless support.

Finally, greatest thanks go to my parents, who sacrifice their life for our success.

Thank you,

Aghil Yari

January 2017

Contribution of Authors

This thesis is submitted in the format of manuscript for journal publication. This thesis format has been approved by the Faculty of Graduate and Postdoctoral Studies, McGill University, and follows the conditions outlined in the "Guidelines for a Manuscript Based Thesis Preparation".

Manuscripts presented in this thesis are prepared by the principle author, Aghil Yari, and co-authored by Prof. Chandra A. Madramootoo, Dr. Viacheslav I. Adamchuk, Hsin-Hui Huang, Laura Gilbert at the Department of Bioresource Engineering, Macdonald Campus, McGill University, Sainte-Anne-de-Bellevue, Quebec, Canada, and Dr. Shelley A. Woods scientist of the Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada.

The principal author was responsible for preparing the experimental design and methodology, conducting the field work, analyzing data, and the documentation. Prof. Chandra A. Madramootoo, is the thesis supervisor who provided valued guidance, suggestions, and proofreading of all manuscripts and the research. Dr. Shelley A. Woods provided the extensive technical assistant for conducting the field experiments over the study period at the Alberta Irrigation Technology Center (AITC). She also provided suggestions and proofreading of all manuscripts. Dr. Viacheslav I. Adamchuk provided the technical suggestions and proofreading of all manuscripts. Mrs Hsin-Hui Huang co-authored the second manuscript (chapter 4). She provided the technical assistant in analyzing the field data. Mrs Laura Gilbert co-authored the fourth manuscript (chapter 6). She provided the assistant in collecting the field data and writing a report for the 2015 growing season.

List of publications and scientific presentations related to the thesis

A. Publications in peer-reviewed journals

1. **Yari, A.,** Madramootoo, C. A., Woods, S. A., Adamchuk, V., 2017. Performance evaluation of constant versus variable-rate irrigation. Journal of Irrigation and Drainage. DOI: 10.1002/ird.2131.
2. **Yari, A.,** Madramootoo, C. A., Woods, S. A., Adamchuk, V., Huang, H. H., 2017. Assessment of field spatial and temporal variability to delineate site-specific management zones for variable-rate irrigation. Journal of Irrigation and Drainage Engineering. (Accepted).
3. Boluwade, A., Madramootoo, C. A., **Yari, A.,** 2015. Application of unsupervised clustering techniques for management zone delineation: Case study of variable-rate irrigation in southern Alberta, Canada. Journal of Irrigation and Drainage Engineering, 142(1), 05015007.
4. Huang, H.-H, Adamchuk, V., Madramootoo, C. A., **Yari, A.,** 2016. An economic assessment tool to optimize the spatial scale of water management using variable rate irrigation. Journal of Agricultural Water Management (Accepted).

B. Thesis chapters submitted for publication in peered reviewed journals

5. Yari, A., Madramootoo, C. A., Woods, S. A., Adamchuk, V., 2017. An assessment of water and energy consumption and crop productivity of variable-rate irrigation; A case study in southern Alberta, Canada. Precision Agriculture. (Submitted).

6. **Yari, A**., Madramootoo, C. A., Woods, S. A., Adamchuk, V., Gilbert, L., 2017. Application of variable-rate irrigation for potato productivity. Irrigation Science. (To be submitted).

C. Non-refereed conference proceedings

7. **Yari, A.,** Madramootoo, C. A., Woods, S. A., Adamchuk, V., 2014. Evaluation and demonstration of the benefits of variable-rate irrigation technology, American Society of Agriculture and Biological Engineers (ASABE), Annual International Meeting, Montreal, Canada, July 13-16, 2014 (oral presentation).
8. Boluwade, A., Madramootoo, C. A., **Yari, A.,** 2014. Establishing management zones and assessing spatial clustering methods for implementation of variable-rate irrigation, American Society of Agriculture and Biological Engineers (ASABE), Annual International Meeting, Montreal, Canada, July 13-16, 2014 (poster presentation).
9. **Yari, A.,** Madramootoo, C. A., Woods, S. A., Adamchuk, V., 2015. Application of variable-rate irrigation technology to improve water conservation and crop productivity. Irrigation Technical Conference, Alberta, Canada, June 9, 2015 (oral presentation).
10. **Yari, A.,** Madramootoo, C. A., Woods, S. A., Adamchuk, V., 2016. Evaluation of water and energy savings and crop production benefits of variable-rate irrigation technology, Canadian Water Resource Association (CWRA), National Conference, Montreal, Canada, May 25-27, 2016 (oral presentation).
11. Huang, H. H., Adamchuk., V., Madramootoo, C. A., **Yari, A., 2016.** Economic optimization of the levels of control in variable-rate irrigation. American Society of Agriculture and Biological Engineers ASABE, IA Symposium: Emerging Technologies for Sustainable Irrigation, Paper No. 152147596, pages 1-15, St. Joseph, Mich.

Table of contents

Table of figures

List of tables

List of abbreviation

AIMM	Alberta Irrigation Management Model
AIPA	Alberta Irrigation Projects Association
AITC	Alberta Irrigation Technology Center
ANOVA	Analysis of Variance
APSIM	Agricultural Production Systems Simulator
ASABE	American Society of Agricultural and Biological Engineers
AWC	Alberta Water Council
CEP	Conservation, Efficiency, and Productivity
CPIS	Center Pivot Irrigation System
CSBE	Canadian Society for Bioengineering
CU	Coefficient of Uniformity
DSSAT	Decision Support System for Agro-technology Transfer
DU_{lq}	Low Quarter Distribution Uniformity
EC_a	Apparent Soil Electrical Conductivity
EC	Electrical Conductivity
ESRI	Environmental Systems Research Institute
ET_o	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FC	Field Capacity

FPI	Fuzziness Performance Index
SED	Stem End Discoloration
GHG	Greenhouse Gas
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
HI	High Irrigation
HR	High Rate
IBM	International Business Machines
IA	Irrigation Association
CU_{HH}	Heermann and Hein Coefficient of Uniformity
MAD	Management Allowed Depletion
MZ	Management Zones
MZA	Management Zones Analyse
MBE	Mean Bias Error
NSERC	Natural Sciences and Engineering Research Council of Canada
NI	Normal Irrigation
NR	Normal Rate
NDVI	Normalized Difference Vegetation Index
NCE	Normalized Classification Entropy
NRMSE	Normalized Root Mean Square Error
PCA	Principal Component Analysis

PWP	Permanent Wilting Point
LESA	Low Elevation Spray Application
LI	Low Irrigation
LR	Low Rate
RCBD	Randomized Complete Block Design
RTK	Real Time Kinematic
REDCAP	Regionalization with Constrained Clustering and Partitioning
RIMCS	Remote Irrigation Monitoring and Control System
RMSE	Root Mean Square Error
RZWQM	Root Zone Water Quality Model
SCL	Sandy Clay Loam
SMRID	St. Mary River Irrigation District
SBC	Single Board Computer
SPSS	Statistical Package for the Social Sciences
SSMZ	Site-Specific Management Zone
SSIM	Site-Specific Irrigation Management
SE	Standard Error
SD	Standard Deviation
SAS	Statistical Analysis System
SCADA	Supervisory Control and Data Acquisition
VFD	Variable-Frequency Drive

VRA	Variable-Rate Application
VRI	Variable-Rate Irrigation
VRLI	Variable-Rate Linear Irrigation
WUE	Water Use Efficiency
WSU	Washington State University

List of symbols

ºC	Celsius degree
$dS\ m^{-1}$	Decisiemens per meter
e_a	Actual vapour pressure (kPa)
e_s	Saturation vapour pressure (kPa)
e_s-e_a	Saturation vapour pressure deficit (kPa)
G	Soil heat flux density ($MJm^{-2}day^{-1}$)
$g\ m^{-3}$	Gram per cubic meter
kPa	Kilo pascal
m	Meter
mL	Millilitre
mm	Millimetre
$m\ s^{-1}$	Meter per second
$mS\ m^{-1}$	Millisiemens per meter
$t\ ha^{-1}$	Tonne per hectare
T	Mean daily air temperature at 2 m height (°C)
Rn	Net radiation at the crop surface ($mMJm^{-2}day^{-1}$)
u_2	Wind speed at 2 m height ($m\ s^{-1}$)
Δ	Vapour pressure curve ($kPa°C^{-1}$)
γ	Psychrometric constant ($kPa°C^{-1}$)
%	Percent

Thesis chapters

This thesis is presented in 8 chapters:

Chapter 1	General Introduction, background, and objectives.
Chapter 2	Literature review of irrigation in Alberta, variable-rate irrigation, management zone delineation, and field variability.
Chapter 3	Performance evaluation of constant versus variable-rate irrigation.
Chapter 4	Assessment of field spatial and temporal variability to delineate site-specific management zones for variable-rate irrigation.
Chapter 5	An assessment of water and energy consumption and crop productivity of variable-rate irrigation; A case study in southern Alberta, Canada.
Chapter 6	Application of variable-rate irrigation for potato productivity.
Chapter 7	Summary and conclusions
Chapter 8	Contribution to knowledge and recommendations for future research

Chapter 1

Introduction

1.1 Introduction

Limited fresh water resources and increasing competition from different water-dependent sectors will negatively affect the world's food production. Globally, irrigated agriculture is the largest consumer of fresh water, and consumes approximately 70% of all annual fresh water withdrawals (UNWWDR, 2014). Improving irrigation efficiency is a continuing global goal to conserve fresh water. There is a need to better match water applications to soil properties and crop requirements in order to reduce water losses and increase crop productivity. Excessive irrigation causes soil waterlogging, salinity, erosion, poor crop quality, plant diseases, and environmental degradation. Recent innovations in sensor technologies and wireless data communication networks in conjunction with advances in internet and mobile application technologies offer extremely essential opportunities for the development of management tools and decision support systems to aid the agriculture sector to improve irrigation efficiency and productivity (Evans et al., 2013; Smith et al., 2010). Over the past few years, variable-rate irrigation (VRI) technology has been developed commercially to control center pivot travel speed, individual sprinkler, and sprinkler banks to apply water differentially to each management zone (Evans and Sadler, 2013). There is increasing interest in the potential benefits that the new technologies can provide in improving water and energy efficiency and crop productivity (Daccache et al, 2015). In addition, VRI is an effective management tool for improving the control of agricultural inputs application in amounts that match the needs of individual homogenous areas within fields (O'Shaughnessy et al., 2011; Perry et al., 2003). Agricultural fields are never spatially and temporally uniform and existing irrigation systems have been developed to apply a uniform depth of water over the entire field without taking the spatial and temporal variability of the field into consideration. As a result, crops in some areas receive more water more than required, and some areas receive less than required. Furthermore, excessive water applications could contribute to surface runoff, leaching of nutrients, wastage of water, disease and environmental degradation (Hezarjaribi, 2008). Evett, et al., (2014) pointed out that the irrigation strategies should be managed site-specifically to be more effective and VRI in particular could be used to reduce the soil water content variability and potential runoff. Furthermore, with the adoption of new control technologies, it is possible to apply agricultural inputs at variable rates to improve a crop yield productivity in low-yielding areas and reduce variability of crop quantity and quality within irrigated fields. However, there are still barriers and challenges that can stand in the way of VRI development. Understanding these barriers and challenges is important when farmers are getting involved to adopt the technology. The focus of this study is to highlight some of the incentives to motivate irrigators to consider the VRI for sustainable agriculture.

1.2 Research objectives

Four-years of field experiments were carried out to evaluate the performance of VRI technology applied to center pivot irrigation system (CPIS) in southern Alberta by accounting field variability to conserve water, optimize energy consumption, and improve crop yields.

This was achieved through the following specific objectives

1. **Performance evaluation of constant versus variable-rate irrigation**

   To address objective one, a variable-rate CPIS consisting of five spans, covering an area of 27 ha at the Alberta Irrigation Technology Centre (AITC) of Alberta Agriculture and

Forestry, in Lethbridge, southern Alberta was used to evaluate and identify the benefits and limitations of commercial VRI technology under constant and variable application rates. The application uniformity and application depth of the five-span CPIS retrofitted with variable rate zone control and low elevation spray application (LESA) were evaluated. Constant and variable application rates were applied to the irrigation system in a windy location under various wind speeds in a grid configuration and along transects with sector angle of 2º.

2. **Assessment of field spatial and temporal variability to delineate site-specific management zones for variable-rate irrigation**

   To address objective two, a stepwise multivariate regression approach was used to investigate how multiple measured parameters affect the crop yield. An unsupervised clustering algorithm, fuzzy C-mean clustering technique, were used to delineate management zones. Fuzziness performance index (FPI) and normalized classification entropy (NCE) were used as verification criteria to determine the optimal number of management zones.

3. **An assessment of water and energy consumption and crop productivity of variable-rate irrigation; A case study in southern Alberta, Canada.**

   To achieve objective three, water and energy savings, and wheat production were evaluated. Specific sub-objectives were to; 1) assess water applications under VRI and non-VRI systems, 2) evaluate of potential energy savings under VRI, 3) investigate wheat yields produced in three management zones under three irrigation treatments, and 4) use AquaCrop model to optimize crop yield production under VRI.

4. **Application of variable-rate irrigation for potato productivity**

To achieve objective four, application of VRI technology was investigated to reduce irrigation water for Russet Burbank potatoes in southern Alberta. To examine the performance of the system the quantity of water applied under the three irrigation treatments, the irrigation frequency, and the energy consumption of the irrigation system were monitored. The effects of different water application rates on potato yield and quality were further assessed.

Chapter 2

Literature Review

2.1 Irrigation in Alberta

Alberta as a capital of irrigation with an irrigated area of about 600,000 ha represents 65% of the total irrigated land in Canada (Alberta Agriculture and Forestry, 2015b). The irrigated agriculture is the largest consumer of Alberta's fresh water and consumes approximately 75% of the total volume of water withdrawals (Corkal and Adkins, 2008). In Alberta, 13 irrigation districts deliver water to over 6,000 water users and the majority of irrigated land situated in the southern part of the province (Alberta Water Council, 2007). Cereal crops and forages are major components of Alberta's agricultural industry with 35% and 31% of all irrigated lands, respectively (Fig. 2.1) (Alberta Agriculture and Forestry, 2014).

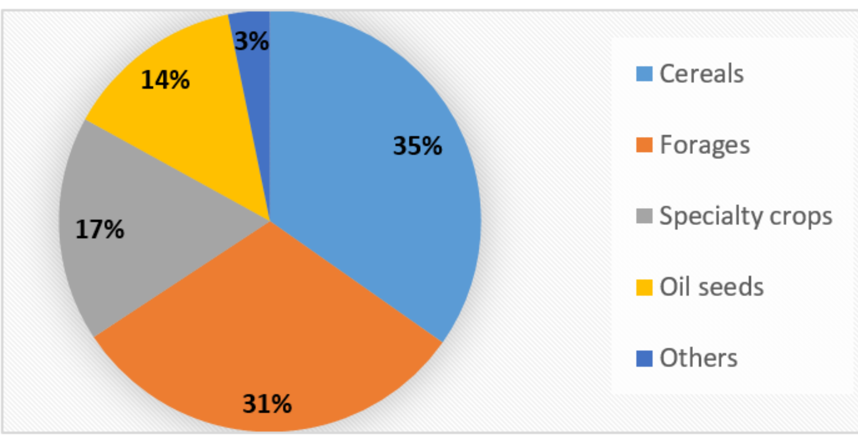


Figure 2.1 Crops grown within the 13 irrigation districts in southern Alberta in 2013 (Specialty crops are: Canola seed, alfalfa, dry beans, potatoes, and sugar beets - Alberta Agriculture and Forestry, 2014)

A variety of on-farm irrigation systems utilized within the 13 irrigation districts in southern Alberta is presented in Figure 2.2. The low-pressure center pivot irrigation systems (CPIS) are the most utilized irrigation systems in southern Alberta and 69% of the irrigators (Alberta Agriculture and Forestry, 2014) have been using this method of irrigation for supplemental and full irrigation. The increasing use of low pressure CPIS in southern Alberta enables farmers to improve water and energy use efficiency and crop productivity. Moreover, advanced technologies such as variable-rate irrigation (VRI), decision support systems, irrigation scheduling applications, and a combination of plant and soil sensors network may provide great opportunities for farmers to optimise water and energy consumption, and improve overall productivity. Generally, application of the most current technologies would benefit the irrigation industry which contributes more than $5 billion to the Alberta economy.

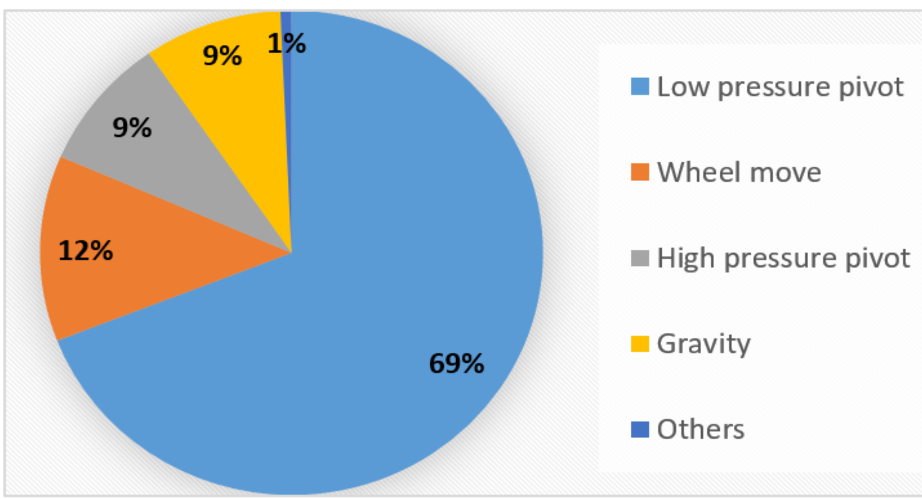


Figure 2.2 On-farm irrigation systems within the 13 irrigation districts in southern Alberta -Alberta Agriculture and Forestry, 2014)

In southern Alberta, where rainfall is insufficient, irrigation is a key for beef industry, forages, and grains production. Irrigation industry, as one of the most profitable sectors in southern Alberta, deserves continues improvement and rehabilitation. Alberta's irrigation sector, under its Water for

Life Strategy, is committed to improving water and energy use efficiency and crop productivity through adoption of new technologies (Alberta Water Council, 2007; Alberta Irrigation Projects Association, 2010). Accordingly, the irrigation sector has stipulated a target of 30% through combination of increase in conservation, efficiency and productivity (Alberta Water Council, 2007). In order to achieve these targets, farmers are required to adopt more advanced on-farm water application technologies that minimize the wastage of water due to excessive surface runoff and deep percolation, both of which contribute to environmental problems of water-logging, soil salinization and non-point source pollution.

2.2 Variable-rate irrigation development and evaluation

Site-specific applications approaches were initiated in the early 1990's using modified center pivot and linear move irrigation systems to apply water and nitrogen to achieve desired application depth. Center pivot and linear move irrigation systems due to high level of automation and control system are an ideal candidate for site-specific management (King and Kincaid, 2004).

Various aspects of VRI were investigated during the last two decades. In 1993, a continually moving irrigation machines were modified for variable water and chemical application across a field (McCann and stark, 1993; Fraisse, et al., 1993; Duke, et al 1992). Modified center pivot and linear move irrigation systems for variable rate applications were developed to control an individual or group of sprinklers, lateral speed, and flow rate of the sprinkler to acknowledge the field variability (Duke et al., 1992; Fraisse et al., 1993; Sadler and Florence, 1994; Fraisse, et al., 1995; Sadler, et al., 1996; Camp and Sadler, 1997b; Camp et al., 1997; McCann et al., 1997; Omary et al., 1997; Camp and Sadler, 1998; King and Wall, 1998).

At the very beginning of the 21st century, the emphasis of research extended to the performance evaluation and demonstration of VRI. Therefore, additional researches have also been undertaken to evaluate the performance of the technology. In 2003, a VRI system was compared with non-VRI system to understand the effect of variable-rate application on irrigation uniformity (Perry and Pocknee, 2003). The VRI system used GPS to coordinate irrigation system position and specific desktop PC software was developed to generate application map for VRI. The result of field experiments indicated that the VRI technology had as good uniformity as the non-VRI system.

Dukes and Perry, (2006) implemented a comprehensive research project to study uniformity and feasibility of VRI with a center pivot and a linear move irrigation systems. The uniformity of application was evaluated at two system travel speeds and three variable-rate settings. Overall, the coefficient of uniformity (CU) and low quarter distribution uniformity (DU_{lq}) averaged 93% and 0.90, respectively, for the center pivot; 84% and 0.74 for the linear move systems. The feasibility of applying spatially variable irrigation under a center pivot system was assessed by Al-Kufaishi et al, (2006) at the Federal German Agricultural Research Center, Braunschweig, Germany. The assessment was based on soil moisture holding capacity, soil depth variation and root development. The results showed that the loss of water was higher for the non-VRI application scenarios than for variable rate applications. O'Shaughnessy et al, (2011) performed uniformity tests to evaluate the application uniformity of a commercial VRI system for a 3-span center pivot at different watering rates (100%, 80%, 70%, 50%, and 30%). Results revealed that the CU and DU_{lq} were significantly lower where application rate was less (30%). Additional work has been undertaken at the Conservation and Production Research Laboratory, Bushland, Texas to evaluate the performance of VRI system in a windy condition (O'Shaughnessy et al., 2013). The results showed that the average CU_{HH} and DU_{lq} in the system travel direction with different water application depths were 88% and 80%, respectively. Wind speeds greater than 5 m s^{-1} negatively impacted the uniformity of water application within the irrigation zones with lower irrigation depth. Most recently, application uniformity of a commercial variable rate centre pivot irrigation system was assessed. Uniformity test under different water application depths indicated that higher application rates resulted higher irrigation uniformity (Sui and Fisher, 2015).

Other recent work at Clemson University involved the development of a variable-rate lateral irrigation system for site-specific application to acknowledge the field variability (Han et al., 2009). Uniformity tests identified that the system was able to control the water application depth from 0 to 25 mm and travel speed between 29 and 145 m h^{-1}. The CU values for four different irrigation depths of 25, 19, 13, and 6 mm were 94, 94.8, 91.7, and 79.5, respectively.

A wireless control system was developed and evaluated at Washington State University (WSU) for site-specific management to monitor and control continuous moving irrigation machines (Chávez et al., 2010a) using a single board computer (SBC) with the Linux operating system. This system was able to control water application rate of individual or groups of sprinklers based on prescribed application maps. Chávez et al, (2010b) assessed the performance of two linear move irrigation systems equipped with the aforementioned wireless control system. This system was able to monitor water application rate, pressure, and wireless field sensors networks. Uniformity tests and field experiments identified that an overall performance of the system was acceptable. Other work at University of Southern Queensland (McCarthy, et al., 2010) has focused on the development of a simulation framework (VARIwise) for evaluation and management of site-specific irrigation control strategies. VARIwise has the capability to generate and implement management strategies for site-specific application using spatial databases and simulation modules.

A wireless computer vision instrument was developed (Casanova et al., 2014) to detect a crop water stress and crop disease stress for VRI proposes. Resent research work (O'Shaughnessy et al., 2016) has expanded to include the use of supervisory control and data acquisition (SCADA) system to integrate of spatial and temporal field variables with VRI to enhance water use efficiency (WUE) for agricultural productivity. Most recently, Andrade et al. (2015) developed a software (ARSmartPivot) as a decision support tool to facilitate communications between users, sensor networks, and irrigation system for site-specific management. This software was able to integrate collected data to generate irrigation prescription map. A smartphone application, web-based irrigation scheduling approaches, site–specific water production functions, SCADA, wireless computer vision instrument, and sensor technology would serve VRI to improve water use efficiency (Casanova et al., 2014; Andrade et al., 2015; Bartlett et al., 2015; O'Shaughnessy et al., 2016; Haghverdi et al., 2016).

The VRI technologies require a high level of management, advanced hardware and software, and prescription maps to apply water across a field based on the spatial and temporal variability of soil attributes, landscape features, and crop conditions (Evans et al., 2013; Stone et al., 2015). Recently, some irrigation companies (Valmont, Lindsay, and Reinke) offer CPIS with speed and zones control options. The speed control allows a CPIS to change application depth in radial sector to meet desired depth in 1^{o} to 10^{o} increments (Evans et al., 2013). The zone control allows the center pivot and lateral-move irrigation system to use individual or group of sprinklers to change the application rate of sprinklers at any given zone (O'Shaughnessy, et al., 2016).

2.3 Water and energy savings and crop production benefits of VRI

Current and past research works were focused on development and performance evaluation of VRI technology. To move toward adoption of VRI technology, determination of the water, energy, and crop production benefits are needed. A few studies have attempted to investigate the potential benefits of VRI technology. The benefits of VRI is very site-specific and strongly depends upon field spatial and temporal variability (Daccache et al., 2015). The VRI technology has the potential to improve the water and energy use and increase economic efficiencies by optimally matching agricultural inputs to yield in pre-defined management zones (Smith et al., 2010). Evidence from studies of VRI supported that water saving of up to 50% can be achieved (Sadler et al., 2005; Hedley and Yule, 2009; Smith et al., 2010; Hedley and Yule, 2012; Charles and Chad, 2014). Yule and Hedley, (2008) investigated the water and energy saving benefits of VRI on a 22 ha farm in New Zealand. The optimum amount of irrigation was applied within three management zones and water savings of 20% to 25% was achieved. Also, the irrigation operating costs dropped by $77-$113 per hectare. The authors pointed out that the impact of VRI on water and energy savings is very site-specific and adequate information is needed for achieving the full potential of VRI technology.

Optimal irrigation management strategies were implemented on three farms in Oregon, Washington, and Idaho within the Columbia Basin, USA, using VRI technology (Charles and Chad, 2014). Deficit irrigation and spatial optimization of water application approaches were employed to improve farm profitability. Results from the study showed water saving ranged from 4% to 8.8% for four different irrigation prescription maps during the 2013 growing season (Charles and Chad, 2014). LaRue, (2011) reported the benefits of a commercial CPIS equipped with the

VRI technology (variable rate zone control package). Overall, 12% less irrigation was applied, and a reduction of 15% in nitrogen was achieved.

There is a potential for yield improvement and increased profitability (Stone et al., 2015) of the irrigated field with VRI strategy. King et al, (2006) highlighted that a site-specific irrigation management (SSIM) has the potential to improve the yield and quality of potatoes in comparison to conventional uniform irrigation management. They reported that total potatoes yields were improved per unit of applied water by 4% and 6% in 2001 and 2002 under the SSIM, respectively. The gross income was $159 per hectare greater in SSIM as well. Similarly, McClymont et al, (2012) found that the SSIM improved yield production in low-yielding areas and reduce yield variability within irrigated filed under drip irrigation system. Modification of irrigation scheduling strategies within three management zones increased yields of a previously low-production area and improved water use efficiency during a five-year study in the Sunraysia region of Australia. Booker et al, (2006) reported an improvement on water use efficiency for cotton field under VRI system during a four-year field experiment.

In general, application of proper irrigation prescription maps, decision support systems, and spatial and temporal field information would assist VRI to reduce negative environmental impacts and increase water and energy efficiency and crop productivity. Furthermore, VRI provides opportunity to improve crop yield in low-yielding areas, reduced occurrences of disease, avoids leaching, and ultimately increase the overall profitability. Obviously, there are many opportunities for expansion of VRI, but there are some barriers to the adoption as well (Evans et al., 2013). The relatively high capital investment is one of the major barriers for the expansion of VRI. However, recent evidence demonstrated that an investment in VRI paid back in the first year by diverting the saved water to the adjacent dryland to irrigate pasture (Hedley and Yule 2012). Ultimately, there remains a knowledge gap with respect to the application of VRI that can be addressed by more research and training programs (Evans et al., 2013).

2.4 Spatial and temporal variability

Spatial and temporal variability such as; soil chemicophysical properties, topography, soil water content, variable rainfall and evapotranspiration distribution during a growing season, and temporary ponding are sources of the crop yield variation in irrigated fields. Implementing site-specific management strategies to overcome field variability can substantially increase crop yields in low-production area and prevent under or over-irrigation. Therefore, the site-specific management is an effective strategy in maintaining that the irrigated agriculture is more productive and profitable through the variable application of agricultural inputs over the entire field. The current trend is to implement the site-specific management zones (SSMZ) approach, rather than the traditional whole field approach to manage within-field spatial and temporal variability (Li et al., 2008). An important aspect of VRI is the defining SSMZ. Delineation of SSMZ or dividing a field into homogenous sub-fields is difficult due to the complex combination of the spatial and temporal variation. Variation in soil chemical and physical characteristics, topographic attributes, and methodological factors contribute a spatial variation in crop yield (Corwin, 2013). For example, topographical variation (e.g. elevation and slope) across a field can cause lateral movement of soil nutrients and water in the soil profile toward low elevation areas (Sadler et al., 2000) and limit the crop productivity in high elevation areas. In addition, highly variable elevation causes an over-application in low elevation areas and under-application in high elevation areas. Moreover, spatial and temporal variability can negatively affect nitrogen dynamics across a field (Khosla et al., 2002). Therefore, spatial variability (topography) in conjunction with temporal variability (soil moisture content) results in an uneven distribution of water application and, consequently, generates a non-uniform soil moisture pattern (Longchamps et al., 2015) over the plant effective root zone. Therefore, spatial and temporal variability can negatively and extensively affect crop yields within irrigated fields.

In most cases, the SSMZ delineation relied on yield limiting factors such as soil salinity, pH, texture, color, fertility, organic matter, and topographic attributes (Fridgen et al., 2000; Hornung et al., 2006; Da Silva et al., 2008; Xin-Zhong et al., 2009; Haghverdi et al., 2015). Soil physical and chemical properties have been the most widely used parameters for site-specific management zone delineation (Khosla et al., 2010). Utilizing all of these factors for SSMZ delineation is so labour intensive and cost-prohibitive in terms of data collection and analysis. Dimension reduction techniques such as a principal component analysis (PCA) and multivariate stepwise regression models can be used to limit the number of variables for effective SSMZ delineation (Xin-Zhong et al., 2009; Kitchen et al., 2003). Fleming et al, (2000) investigated the effectiveness of the farmer developed management zones using limited data (e.g. soil color, topography, and farmer experience). It is identified that the farmer developed management zones may be effective and economical compared to an intensive grid soil sampling to develop prescription maps for variable rate fertilizer application. Similarly, Pelcat et al, (2004) developed management zones for variable rate fertilizer application from remote sensing imagery. In addition, yield information (e.g. normalized difference vegetation index (NDVI) and multispectral images) in combination with soil EC can be used to define management zones (Li et al., 2008; Bellvert et al., 2012).

The application of apparent soil electrical conductivity (EC_a) and topographic attributes for SSMZ delineation have been widely investigated (Fraisse et al., 2001; Kitchen et al., 2005; Li et al., 2007; Molin and Castro, 2008). Topographic attributes and EC_a are indicators of plant-available water and useful in management zone delineation (Fridgen et al., 2000). It is very cost effective and rapid to use on-the-go soil sensor technology (Adamchuk et al., 2004) to record geo-referenced EC_a and physical geographic features for SSMZ delineation. Recently, due to the development of on-the-go soil sensor technology, geo-referenced EC_a and field elevation have been widely adopted for SSMZ delineation (Fraisse et al., 2001; Kitchen et al., 2003; Kitchen et al., 2005; Li et al., 2007; Miller et al., 2014; Gavioli et al., 2016).

Temporal variation such as soil water content, water holding capacity, irrigation deficit, crop water stress, diseases, rainfall, and temporary ponding can also cause a significant crop yield reduction (Evans and Sadler, 2013). These factors can be used for development of SSMZ and variable rate application maps (Corwin, 2013; Pan et al., 2013; Casanova et al., 2014). Most recently, dynamic prescription maps were developed using a plant feedback system for cotton field irrigating with a center pivot irrigation system (O'Shaughnessy et al., 2015). A wireless network of infrared thermometers was used to monitor crop water stress for triggering an irrigation for the experimental plots. The plant feedback technology can facilitate the use and adoption of VRI by providing dynamic prescription maps during the crop growing season (O'Shaughnessy et al., 2015).

2.5 Management zones delineation

A different number of approaches with different attributes have been used to delineate management zones for SSMZ delineation. Management Zone Analyst (MZA) model developed by Fridgen et al, (2004) was widely used to identify SSMZ based on spatial and temporal variables (Li et al., 2007; Molin and Castro, 2008; Zhang et al., 2010) . The fuzzy C-mean unsupervised clustering algorithm is adopted to cluster data into different homogenous regions (Odeh et al., 1992; Fridgen et al., 2004). Fuzziness performance index (FPI), representing the least membership sharing, and normalized classification entropy (NCE), representing greatest amount of organization, were used as a verification criterion to determine the optimal number of management zones by fuzzy C-mean clustering algorithm.

Pelcat et al, (2004) employed the fuzzy C-means algorithm as a clustering technique and found that satellite imagery generated the best SSMZ in terms of cost. A web-based zone mapping application has been developed (Zhang et al., 2010) to identify the optimal number of SSMZ using a remote sensing imagery and field data. Boluwade et al. (2016) investigated a fuzzy C-means algorithm and regionalization with constrained clustering and partitioning (REDCAP) technique for delineating management zones using EC_a and elevation maps. The study found that the fuzzy C-means algorithm using MZA software generated the cost effective solution for delineating management zones.

2.6 Crop modeling and VRI

Crop production has improved considerably by using the new technologies and simulation models during the last few decades. Crop simulation models were developed to investigate the complex relationship between crop yield and water use through the use of simplified methods and limited information (DSSAT, RZWQM, APSIM, and AquaCrop). FAO (Food and Agriculture Organization of the United Nations, Rome) developed and released the first version of AquaCrop model in 2009 to assess yield response to water. The AquaCrop model was developed using the equation of Doorenbos and Kassam (Doorenbos and Kassam, 1979) to optimize crop yield in response to water use and water deficit. The model provides proper management strategies to improve the efficiency and productivity of water for crop production.

The AquaCrop model simulates biomass and yield production under different irrigation scenarios, management practices, and soil fertility and salinity. Accurate prediction of parameters by dynamic crop simulation models depend on available data and model calibration and validation. Field experiments were carried out (Abedinpour et al., 2012) to evaluate the performance of AquaCrop model at the research farm of the Water Technology Center, New Delhi, India, for maize crop under different irrigation and nitrogen application levels from 2009 to 2010. Calibration and validation were performed using 2009 and 2010 data, respectively. Overall, the model simulated grain and biomass yield with acceptable accuracy and the model prediction error for predicting the water productivity varied between 2.35% and 27.5%. The AquaCrop model performance was tested in simulating biomass and yield of water deficient and irrigated barley during the growing seasons of 2006, 2008, and 2009 at Mekelle site in northern Etiopia (Araya et al., 2010). The model was able to simulate the soil water in the root zone, biomass, and grain yield of barley under various planting dates and water availability conditions.

This model has been used for different crops under different water deficit strategies and environmental conditions. Singh et al, (2013) investigated the AquaCrop model for simulating of an irrigated wheat production in West Bangal, India, with 10 varieties of wheat from 2008 to 2010. The model was used (Andarzian et al., 2011) to evaluate wheat production under full and deficit irrigation regimes in a hot dry environment condition in south of Iran. The model simulated soil water content of root zone, crop biomass, and grain yield, with normalized root mean square error (NRMSE) of less than 10%.

The AquaCrop model in combination with an economic model has the potential to assist farmers and decision makers on cropping pattern and irrigation management (García-Vila and Fereres, 2012). The model was successfully used to evaluate the impact of different management strategies on farm income in South-Western Spain (García-Vila and Fereres, 2012).

2.7 Potatoes in Alberta

Russet Burbank potato is a chipping variety common to the province of Alberta. For Russet Burbank potato, available soil water (ASW) of the root zone below 65% from planting to tuber bulking can result in lower yields (King and Stark, 1997). At the planting stage, recommended ASW is 70-80%. Excessively wet or dry soils will increase seed decay. Cold soils resulting from overwatering delay sprouting (King and Stark, 1997). During vegetative growth, tuber initiation, and tuber bulking, the recommended ASW is 65-85% (King and Stark, 1997). A water deficit in stages 2-4 reduces leaf and stem development, affecting the rate of photosynthesis and reducing tuber development (King and Stark, 1997). A lower internal water pressure also results in malformations, which reduce tuber quality (King and Stark, 1997). During maturation, the water requirements are lower and ASW should be kept to 60-65% (King and Stark, 1997). Overwatering during skin development will result in enlarged lenticels, which create pathways for soft rot bacteria to enter the tuber (King and Stark, 1997). Prior to harvest, the field should be irrigated to increase ASW to 65% (King and Stark, 1997). Dry soil at harvest increases shattering and makes separation of tuber and soil more difficult (Alberta Agriculture and Forestry, 2011).

Potatoes have high water sensitivity and require a total of 400-550 mm of water supplied by rainfall and irrigation per growing season (King and Stark, 1997). The potato has limited ability to store water for use in dry periods. Excess water results in reduced aeration, stimulating diseases propagation and increasing nitrogen leaching (King and Stark, 1997).

Sugar content is an important indicator of tuber quality. For chipping potatoes, glucose content of less than 0.33% is preferred (Storey and Davies, 1992). A specific gravity of at least 1.08 is preferred for French fries and of 1.085 for chipping (Storey and Davies, 1992). Potatoes have a moderate tolerance to saline soils characterized by an EC of 2 to 4 dS m^{-1} (Alberta Agriculture and Forestry, 2001).

2.8 Conclusions of literature review

According to the literature, research to date has resulted in the development of VRI technology to improve overall productivity of irrigated agriculture. VRI technology is becoming increasingly in demand due to the limitations of conventional irrigation practices. Current irrigation systems are designed for uniform water application. A disadvantage is that this uniformity of application does not account for spatial and temporal variability. Consequently, there is ponding of water in low elevation areas, and surface runoff from the higher elevations. Such situations lead to over-irrigation, and under-irrigation in various field locations. The effect is variability in crop yields, which reduces crop productivity. VRI technology has the potential to improve crop productivity and water and energy conservation, taking spatial variability of soil properties and landscape features into account. More than two decades of research on VRI technology has resulted in limited adoption of the technology due to lack of documented benefits of VRI (Evans et al., 2013). Greater adoption of VRI will require further research efforts, which is currently limited. There is critical need to identify the potential benefits of VRI technology to motivate farmers to move toward adoption of the technology. Research so far has contributed to the development and improvement of hardware and basic zone control software (Evans et al., 2013). Considerably more research will need to be done to identify the potential benefits of VRI technology. This project therefore seeks to assess the performance of VRI, to investigate field spatial and temporal variability for delineating irrigation management zones, and to quantify the potential water and energy savings, and crop productivity benefits of VRI for two crop types in southern Alberta.

Connecting text to Chapter 3

This Chapter is a manuscript published in Journal of Irrigation and Drainage. The manuscript is co-authored by Dr. Chandra A. Madramootoo, Shelley A. Woods, and Viacheslav I. Adamchuk. All literature cited in this chapter is listed in the reference at the end of this thesis.

This chapter covers the performance evaluation of constant versus variable-rate irrigation and therefore discusses objective one of this research. As presented in Chapter one, this paper addresses the knowledge gap in the performance of VRI in southern Alberta. This is the topic of the following article:

"Performance Evaluation of Constant versus Variable-Rate Irrigation"

Contributions made by the different authors are as follows;

1. Aghil Yari, Ph.D. candidate, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
2. Chandra A. Madramootoo, the thesis supervisor, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
3. Shelley A. Woods, Irrigation and Farm Water Division, Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada.
4. Viacheslav I. Adamchuk, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.

The principal author was responsible for preparing the experimental design and methodology, conducting the field work, analyzing data, and the documentation. Prof. Chandra A. Madramootoo, is the thesis supervisor who provided suggestions and proofreading of the manuscript. Dr. Shelley

A. Woods provided the extensive technical assistant for conducting the field experiments. She also provided suggestions and proofreading of the manuscript. Dr. Viacheslav I. Adamchuk provided the technical suggestions and proofreading of the manuscript.

Chapter 3

Performance Evaluation of Constant versus Variable-Rate Irrigation

Aghil Yari[1], Chandra A. Madramootoo[2], Shelley A. Woods[3], Viacheslav I. Adamchuk[4]

[1, 2, 4] Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.

[3] Irrigation and Farm Water Division, Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada.

Abstract

Variable-rate irrigation (VRI) can increase water use efficiency and productivity by applying water based on site-specific needs. In this study, the performance of a five-span center-pivot irrigation system (CPIS) retrofitted with a commercial VRI package was evaluated with constant and variable application depths at the Alberta Irrigation Technology Centre (AITC) in southern Alberta, Canada. Two sets of experiments were designed to investigate the uniformity of application of the system during the 2013 and 2014 growing seasons. The first set of catch-can trials were carried out with three irrigation rates in the direction of pivot travel. Three different wind regimes were observed during the catch-can trials. Catch-cans were arranged in grid configurations within the experimental plots located under one irrigation zone in span 4. The Christiansen coefficient of uniformity (CU) ranged from 90.4 - 94.4%. Wind speeds of 3.3 m s^{-1} and 6.5 m s^{-1} negatively and significantly impacted the CU values. The second set of catch-can trials were performed with used and new sprinklers in a transect along the pivot lateral during the 2014 growing season. The Heermann and Hein coefficient of uniformity (CU_{HH}) ranged from 89.0 - 93.5% and 81.7 - 94.4% with constant and variable application depths, respectively. The greatest

(94.4%) and least (81.7%) CU_{HH} values were observed where water applications were 100% and 40% of the set point, respectively. Overall, the uniformity of application of CPIS retrofitted with the commercial VRI package both along the system's lateral and in the travel direction were above 90% for the majority of the trials under the different wind speeds and water application depths.

Key words: Zone control, center-pivot irrigation, water use efficiency, water productivity, wind speeds, uniformity of application.

3.1 Introduction

In southern Alberta, irrigators are the largest consumers of fresh water and consume, on average 60 to 65% of the total water allocation for irrigation purposes within 13 irrigation districts (Alberta Water Council, 2007). The irrigation industry plays an essential role in increasing crop productivity (Bennett and Harms, 2011) in Alberta. A center-pivot irrigation system (CPIS) with low-pressure sprinkler package is the most popular irrigation method in southern Alberta, used by 70% of the farmers (Alberta Agriculture and Forestry, 2014). The increasing use of CPIS in southern Alberta enables farmers to improve water and energy use efficiency by converting or modifying existing irrigation systems to low-pressure (Alberta Water Council, 2007) and variable-rate irrigation (VRI) technology.

The implementation of new technologies requires comprehensive assessment in order to smooth the process of technology transfer and adoption. Research on site-specific application of water by center-pivot and lateral-move irrigation systems has been ongoing for the last two decades (Al-Kufaishi et al., 2006; Camp et al., 1997; Camp et al., 2001; Dukes and Perry, 2006; King et al., 2005; LaRue, 2011; Lu et al., 2005; O'Shaughnessy et al., 2011, 2013; Omary et al., 1997; Sadler et al., 2000). Application uniformity and accuracy of application depth are two criteria which are used to assess irrigation system performance. The performance of VRI Zone Control with 15 sprinkler banks was evaluated (Dukes and Perry, 2006) with a CPIS at the University of Georgia, and a linear-move irrigation system at the University of Florida. Overall, the Christiansen coefficient of uniformity (CU) and low quarter distribution uniformity (DU_{lq}) averaged 93% and 90%, respectively, for the CPIS; and 84% and 74% for the linear-move system.

The VRI system requires a high level of management, advanced hardware and software, and water application maps; delineated based on spatial and temporal variability of soil and climate conditions. Han et al., (2009) developed and evaluated a variable-rate linear irrigation (VRLI) system for site-specific application. The CU values for four different irrigation application depths of 25, 19, 13, and 6 mm were 94.0%, 94.8%, 91.7%, and 79.5%, respectively. Generally, for center pivot and linear move systems, a coefficient of uniformity ranging from 85-95% would be acceptable. O’Shaughnessy et al. (2011) carried out catch-can tests to evaluate the application uniformity of a three-span CPIS at different irrigation depths (25.4, 20.3, 17.8, 12.8, and 7.6 mm). Results revealed that the average Heermann and Hein uniformity coefficient (CU_{HH}) (85.1%) and DU_{lq} (80%) values were substantially lower when the water application depth was 7.6 mm. O’Shaughnessy et al. (2011) pointed out that the low application uniformity can be related to changes in wind direction and high wind speed. In another study, the application uniformity of the three-span and six-span center pivots equipped with a VRI package and a fixed plate sprinkler under windy conditions was assessed by O'Shaughnessy et al. (2013). The average CU_{HH} and DU_{lq} in the system travel direction with different water application depths were 88% and 80%, respectively. Wind speeds greater than 5 m s^{-1} negatively impacted the uniformity of water application within the irrigation zones with lower irrigation depth.

The main objective of this study was to evaluate performance of a five-span center pivot irrigation system retrofitted with a commercial VRI package under constant and variable application depths. Specific objectives were; to evaluate the application uniformity and application depth of the system equipped with a low elevation spray application (LESA) sprinkler package in the pivot travel direction within the experimental plots in 2º sector angles; to assess the application uniformity along the entire irrigation lateral with constant and variable application depths with used and new sprinkler packages; and to identify the effects of variable application depths and various wind speeds on application uniformity and measured water depths.

3.2 Materials and Methods

3.2.1 Field location and climate

The study was conducted on an 81 ha farm at the Alberta Irrigation Technology Centre (AITC) located in southern Alberta at latitude 49.69º N and longitude 112.74º W with a mean elevation of 905 m above mean sea level. The experimental site has a sandy clay loam (SCL) soil and is approximately 1.6 km east of the city of Lethbridge (Fig. 3.1) within the St. Mary River Irrigation District (SMRID). The SMRID is one of the 13 irrigation districts situated in southern Alberta. It extends over 137,000 ha and is irrigated by water withdrawn from the St. Mary River (Alberta Agriculture and Forestry, 2014). The study site has a semi-arid climate with an average maximum growing season temperature of 21°C and an average minimum growing season temperature of 6°C over the period 2000-2015 (The growing season in Alberta begins in late April and is completed by the end of September) (Alberta Agriculture and Forestry, 2015a). The mean growing season precipitation is 297 mm over the period 2000-2015 (Alberta Agriculture and Forestry, 2015a).

Seasonal rainfall, reference evapotranspiration (ET_o), and irrigation are presented in Table 3.1 for the two years field study (Lethbridge demo-farm weather station).

3.2.2 Center pivot irrigation system (CPIS) and variable-rate irrigation (VRI)

A five-span CPIS (Valley pivot, model 8000) with a lateral length of 294 m located at the east side of the experimental station was used for the field experiments. The five-span CPIS irrigates a 27 ha field. The system is equipped with the LESA sprinkler package, Nelson rotator sprinkler nozzles (R3000, D6-Red), and each sprinkler was fitted with 1.2 bar pressure regulator (Nelson irrigation, Walla Walla, Washington, USA). The irrigation system was retrofitted with VRI zone control package from Valmont (Valmont Industries Inc, Omaha, Nebraska, USA) with 129 sprinklers divided into 12 sprinkler banks. Each sprinkler bank was configured to have 10-12 sprinklers which are controlled with a single electric solenoid valve. The solenoid valves turn sprinkler banks ON and OFF to maintain a water application depth as defined in the irrigation prescription maps. Experimental plots in 2013 were situated under a single sprinkler bank that had 10 sprinklers (sprinkler package was 15 years old) with flexible drop hoses spaced 2.29 m apart, and approximately 1.5 m above the ground. Pivot pressure started with 240 kPa at the center point and ended with 210 kPa at the end of the lateral. Pressure regulators were used to maintain the sprinklers' pressure at 120 kPa.

3.2.3 Experimental setup in 2013

In the 2013 growing season, three water application depths were imposed on the experimental plots and these were all applied randomly in three replicates, resulting in 9 plots. The three water application depths included three different water depths: Normal Rate (NR), Low Rate (LR), and High Rate (HR). The NR treatment was a water application depth of 25.4 mm (recommended by

Alberta Agriculture and Forestry, 2013), and the LR was a water application of 75% of the NR (19.1 mm). The HR was a water application depth of 25% greater than the NR (31.7 mm).

The experimental plots were trapezoidal and each experimental plot measured 24 m long and 7 to 8 m wide and had an area of 192 m^2. The experimental plots were under the sprinkler bank # 9 located at the 4th span from the central tower in quadrant one (north west quadrant) and, sprinkler banks # 8 and 10 were selected as buffer zones around the experimental plots with water application depths identical to the adjacent experimental plots. Thus, three sprinkler banks were selected and programmed to apply water at the same rate over the experimental plots and buffer zones for purposes of the catch-can tests. Three replicates of the three water application depths were randomly allocated to the experimental units in the direction of pivot travel (Fig. 3.2).

The three water application depths were prescribed (See Appendix A and B) and uploaded through the VRI prescription software (Version 6.5, Valmont Industries Inc., Omaha, Nebraska, USA) to the CPIS. The VRI prescription software allows the user to generate water application maps and provides the ability of creating multiple prescription maps based on the site-specific needs.

For purposes of the uniformity tests, 16 catch-cans (10.5 cm diameter, 20 cm tall) were placed in each plot perpendicular to the travel direction of the pivot system to measure the amount of applied water, and to calculate the application uniformity. The catch-cans were positioned in a grid pattern spaced 3 m by 3 m in each experimental plot at a height of 80 cm above ground. To minimize the effect of evaporation from catch-cans during the trials, the volume of collected water was measured as soon as irrigation was completed on the experimental plots.

3.2.4 Experimental setup in 2014

Additional catch-can tests were carried out along the entire irrigation lateral with constant and variable application depths in June 2014. The existing sprinkler package had been used for 15 years, so a new sprinkler package (Nelson rotator sprinkler nozzles R3000, D6-Red) was installed in July 2014 and additional catch-can tests were performed in September 2014, to compare the system performance with the new (2014) and used (2000) sprinkler package. In addition to sprinkler package update, the stand pipe option was used to reduce off duty cycle lag time on sprinkler banks where it takes more than a few seconds for sprinkler valves to close (Valmont Industries Inc, 2013).

Catch cans were established in two lines (Fig. 3.3) along the pivot lateral with a 4 degree interval, at 250º and 254º. Catch cans were arranged in each line, approximately 3 m apart, from spans 2 to 5 of the five-span CPIS. The three different water application depths were programmed along the CPIS lateral in the radial direction and a prescription map was uploaded to the control panel.

On June 10 and 13, 2014, three water depths of 8.1, 14.2, and 20.3 mm were delivered in 4, 3, and 3 sprinkler banks, respectively to measure the application uniformity along the entire center pivot lateral with variable application depths. A water application depth of 15.2 mm was applied to assess the constant rate application performance in non-VRI mode with the old sprinkler package. The mean wind speed during the test was 2.4 m s^{-1}.

Following the installation of the new sprinkler package in July 2014, two lines of catch cans were placed along the pivot lateral with a 4 degree interval, at 82º and 86º under spans 2, 3, 4, and 5 in September 2014. To evaluate the new sprinkler package performance with constant and variable application depths, two tests were performed on September 4 and 9, 2014. A water application of

15.2 mm was applied for the constant rate application test and three water depths of 8.1, 14.2, and 20.3 mm were applied in 4, 3, and 3 sprinkler banks, respectively for the variable rate application test.

3.2.5 Statistical analysis

An analysis of variance (ANOVA) was performed using SAS 9.4 (Institute Inc., Cary, NC, USA) to determine the effects of wind speeds and irrigation treatments on application uniformity and measured water depths.

3.2.6 Evaluation criteria

All catch-can trials were performed based on the standard test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles (ASABE, 2007).

The normalized root mean square error (NRMSE) and mean bias error (MBE) were used to indicate the accuracy between prescribed and observed irrigation depths for each experimental plot:

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(d_i - \hat{d}_i\right)^2}{n}}}{d_{ave}} \quad (3\text{-}1)$$

$$MBE = \left[\sum_{i}^{n}(d_i - \hat{d}_i)\right] / n \quad (3\text{-}2)$$

where n is the number of irrigation depth, i is the ith depth, d is the observed depth of water, $\hat{d}$ is the corresponding prescribed depth of water to be applied, d_{ave} is mean observed depth.

Application uniformity was calculated for each experimental plot using the Christiansen uniformity coefficient (CU) equation (ASABE, 2007):

$$CU = 100 \times \left[1 - \frac{\sum_{i=1}^{n} \left| d_i - \bar{d} \right|}{\sum_{i=1}^{n} d_i} \right] \quad (3\text{-}3)$$

where n is the number of catch-cans, i is the i^{th} catch-can, d is the depth of water collected in the i^{th} catch-can, and $\bar{d}$ is the average of collected water.

Application uniformity was calculated for CPIS using the Heermann and Hein uniformity coefficient (CU_{HH}) equation (ASABE, 2007):

$$CU_{HH} = 100 \times \left[1 - \frac{\sum_{i=1}^{n} S_i \left| d_i - \bar{d} \right|}{\sum_{i=1}^{n} S_i d_i} \right] \quad (3\text{-}4)$$

where S_i is the distance of the i^{th} catch-can from the pivot point.

3.3 Results and discussion

3.3.1 Climatic and experimental conditions

The 2013 catch-can trials were carried out during the three irrigation events on August 19, 21, and 27. Three different wind regimes were observed during the trials. The three wind speeds values were representative of the prevailing climatic conditions at experimental site (W1, W2, and W3 represent wind speeds of 2.4 m s^{-1}, 3.3 m s^{-1}, and 6.5 m s^{-1}, respectively).

In 2013 and 2014, the average air temperature during the tests ranged from 3º C and 12º C. The system operation pressure at the pivot point approximately varied from 240 to 300 kPa for constant and variable application depths.

3.3.2 Field results for 2013

The NRMSE and MBE were calculated between the observed and prescribed depths for three treatments under three wind speeds (W1, W2, and W3) (Table. 3.2). The NRMSE values varied from 0.24 to 0.49 under the wind speeds of 3.3 m s^{-1} and 6.5 m s^{-1}, respectively, and less than 0.25 under a wind speed of 2.4 m s^{-1}. The average NRMSE between the measured depth and prescribed depth were 0.21, 0.38, and 0.34 for LR, NR, and HR treatments, respectively. The MBE values between the measured and prescribed depths ranged from 1.12 mm to 9.62 mm for all water application treatments. The lowest mean MBE (2.45 mm) was for LR, and greatest mean (6.86 mm) was for the HR treatment.

The average water depth in each treatment was calculated. The mean observed and prescribed water depths under the three wind speeds are plotted in Figure 3.4. The mean water depths and standard deviation for LR, NR, and HR treatments under the three wind speeds are presented in

Table 3.3. The mean measured water depths were 20.8, 21.0, and 24.9 mm for LR, NR, and HR, respectively under the three wind speeds. The system delivered 8.7% more water for the LR treatment and 17.5% and 21.6% less water for the NR and HR treatments, respectively. The VRI system loses accuracy when the system tended to deliver higher water application depths within the experimental plots located in a sector angle of 2º. Higher wind speeds (W2 and W3) positively influenced the mean water application depth in the LR treatments, but negatively impacted the mean water depths measured in the NR and HR treatments.

The results obtained from the catch-can tests indicated that the CU values ranged between 90.4% and 94.4% under the three wind speeds (Fig. 3.5). Greater CU values were observed for the catch-can trials conducted at a wind speed of 2.4 m s^{-1} (the CU values were between 93.4% and 94.4%). The CU values were less at the wind speed of 3.3 m s^{-1} and 6.5 m s^{-1} being between 90.4% and 92.4%. The greatest CU value (94.4%) was observed when the wind speed was 2.4 m s^{-1} under the NR treatment. On the other hand, low CU values were observed for the catch-can trial when the wind speed was 6.5 m s^{-1}. Overall, the uniformity of application of the system was more than 90% for the majority of trials under the three wind speeds (Table 3.4).

The statistical analysis identified that the measured water depths in the experimental plots were significantly (confidence level of 0.95) influenced by the three different wind speeds. The wind speed of 3.3 m s^{-1} and 6.5 m s^{-1} negatively and significantly ($P<0.05$) affected application uniformity in the experimental plots. Water application treatments did not significantly influence application uniformity within the experimental plots (Table 3.5).

3.3.3 Field results for 2014

3.3.3.1 Constant irrigation

The first test on June 10, 2014 evaluated the application uniformity of the system with a constant irrigation depth. Measured water depths for the catch-can tests are plotted in Figure 3.6. The prescribed and average measured depths for the catch-can test were 15.2 mm and 13.8 mm, respectively. The mean CU_{HH} value and NRMSE were 89% and 0.23, respectively under the used sprinkler package. The second test was carried out on September 4, 2014 to evaluate system performance with the new sprinkler package. The prescribed and average measured depths for the catch-can test were 15.2 mm and 14.5 mm, respectively. The mean CU_{HH} value and NRMSE were 93.5% and 0.11, respectively for the new sprinkler package. The measured water depths for the used sprinkler package fluctuated in the catch-cans nearest to and furthest from the pivot point. Based on the results, the system performance improved with the new sprinkler package. The water application error decreased by 0.6 mm and the CU_{HH} value increased by 4.5%. These tests were performed on two different dates, but at the same time of day with similar air temperature and wind speed.

3.3.3.2 Variable-rate irrigation

Application uniformity results from the catch-can tests on June 13 and September 9, 2014 revealed that the system with variable application depths, equipped with the new sprinkler package, produced greater CU_{HH} values compared to the used sprinkler package. The mean CU_{HH} values within all three variable application depths with the new and used sprinkler package were 91.8% and 87.6%, respectively. The greatest CU_{HH} value (94.4%) and lowest NRMSE value (0.07) were achieved with the 20.3 mm irrigation depth with the new sprinkler package. The VRI system in this research project was evaluated under the LESA package. Sui and Fisher (2015) and O'Shaughnessy et al. (2013) reported the high application uniformity with the 100% irrigation rate under a fixed-pad sprinkler package. Application uniformity was poor under the low irrigation depth (8.1 mm) for the used sprinkler package and had the lowest CU_{HH} value (Table 3.6). The new sprinkler package increased the water application depth (Fig. 3.7). The CU_{HH} values were improved with the replacement of the new sprinkler package under 8.1, 14.2, and 20.3 mm irrigation depths by 11.2%, 1.5%, and 4.4%, respectively. Overall, the application uniformity with and without VRI tended to be higher, and the system performed well within the acceptable range according to previous studies reported by Gossel et al. (2013), O'Shaughnessy et al. (2011, 2013), and Sui and Fisher (2015) with a commercial VRI package.

3.4 Conclusions

The performance of a five-span center-pivot irrigation system (CPIS) retrofitted with VRI package was evaluated with different water depths during 2013 and 2014, under constant and variable application depths. In 2013, measurements for the catch-can trials happened to be taken at times with three different wind speeds. The measured water depths in the experimental plots were significantly influenced by wind speeds. Wind speeds of 3.3 m s^{-1} and 6.5 m s^{-1} negatively affected application uniformity. The application uniformity was not impacted with the three different water application treatments (LR. NR, and HR) in the direction of pivot travel.

System performance improved with the updating of the sprinkler package under both constant and variable rate applications. The newer sprinkler package improved application uniformity between 1.5% and 11.2% along the pivot lateral under constant and variable application depths. It is necessary to be aware of the age, wear, and functionality of equipment, as it can impact the overall performance of a CPIS.

Further catch-can tests during the 2014 growing season along the pivot lateral revealed that the greatest CU_{HH} values and lowest NRMSE values were achieved with the 20.3 mm irrigation depth with both the new and used sprinkler packages. Application uniformity was poor with 8.1 mm irrigation depth the for the used sprinkler package. The mean application uniformity for the variable and constant application depths with new sprinkler package were 93.2% and 93.5%, respectively. It can be concluded that the application uniformity of the CPIS was not impacted by variable application depths along the entire pivot lateral.

Finally, more catch-can studies are recommended to evaluate VRI performance within the different sector angles.

3.5 Acknowledgement

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for financial support and they would like to extend their appreciation to Alberta Agricultural and Forestry and the Alberta Irrigation Technology Center staff for providing equipment and extensive in-kind support. The authors are also grateful to Rod Bennett director of Irrigation Management Branch, Alberta Agricultural and Forestry, and also Jeff Bronsch, Jim Parker, and Mike Ellefson for their technical support.

Table 3.1 Rainfall, reference evapotranspiration, and irrigation for the 2013 and 2014 growing seasons

Year	ET_o (mm)	Rainfall (mm)	Irrigation (mm)
2013	556	300	90
2014	562	341	106

Table 3.2 The 2013 NRMSE and MBE between the measured and prescribed depths (W1: wind speed of 2.4 m s^{-1}, W2: wind speed of 3.3 m s^{-1}, W3: wind speed of 6.5 m s^{-1}, LR: low rate, NR: normal rate, HR: high rate)

	NRMSE			MBE (mm)		
Treatments	W1	W2	W3	W1	W2	W3
LR	0.11	0.24	0.28	-4.85	-1.38	1.12
NR	0.25	0.43	0.47	1.67	4.60	7.07
HR	0.19	0.33	0.49	4.28	6.68	9.62

Table 3.3 The 2013 mean and standard deviation (Mean ± Std Dev) of measured depths (mm) in all treatments under the three wind speeds (W1: wind speed of 2.4 m s^{-1}, W2: wind speed of 3.3 m s^{-1}, W3: wind speed of 6.5 m s^{-1}, LR: low rate, NR: normal rate, HR: high rate)

Treatments	Prescribed Depths (mm)	W1	W2	W3
LR	19.10	23.90 ± 2.54	20.43 ± 1.04	17.93 ± 0.85
NR	25.40	23.73 ± 1.57	20.80 ± 1.13	18.33 ± 1.17
HR	31.75	27.47 ± 2.10	25.07 ± 1.81	22.13 ± 1.53

Table 3.4 The mean CU values in all treatments under the three wind speeds (2013) (W1: wind speed of 2.4 m s^{-1}, W2: wind speed of 3.3 m s^{-1}, W3: wind speed of 6.5 m s^{-1}, LR: low rate, NR: normal rate, HR: high rate)

Treatments	W1	W2	W3
LR	93.37	91.87	90.37
NR	94.40	90.73	90.50
HR	94.23	92.37	92.30

Table 3.5 P–Values for effects of wind speeds and water application treatments on measured depths and CU values (W1: 2.4 m s^{-1}, W2: 3.3 m s^{-1}, W3: 6.5 m s^{-1}, LR: low rate, NR: normal rate, HR: high rate)

	HR vs LR	HI vs NR	NI vs LR	W1 vs W3	W1 vs W2	W2 vs W3
Depths	<.0001*	<.0001*	0.7953	<.0001*	0.0011*	0.0028*
CU	0.3086	0.3134	0.9917	0.0117*	0.0385*	0.5747

* Significant with confidence of 0.95

Table 3.6 The 2014 CU and NRMSE values for catch-can tests for variable application depths

Prescribed depths (mm)	8.1		14.2		20.3	
Sprinkler package	Used sprinklers	New sprinklers	Used sprinklers	New sprinklers	Used sprinklers	New sprinklers
Mean observed depth (mm)	8.6	10.1	15.4	17.0	17.3	21.0
NRMSE	0.23	0.18	0.13	0.13	0.12	0.07
CU_{HH} (%)	81.7	92.9	90.9	92.4	90.0	94.4

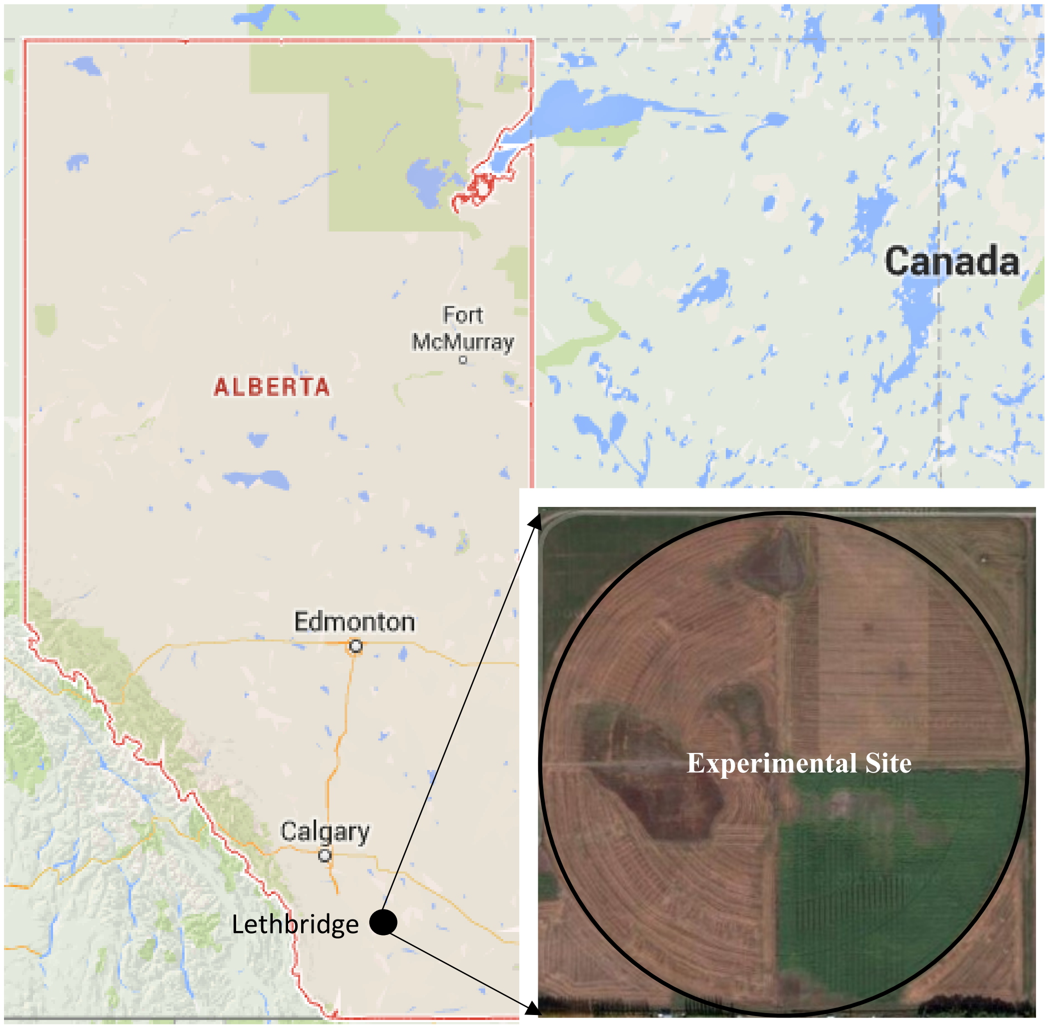


Figure 3.1 Experimental site location ((map data: Google, digital globe)

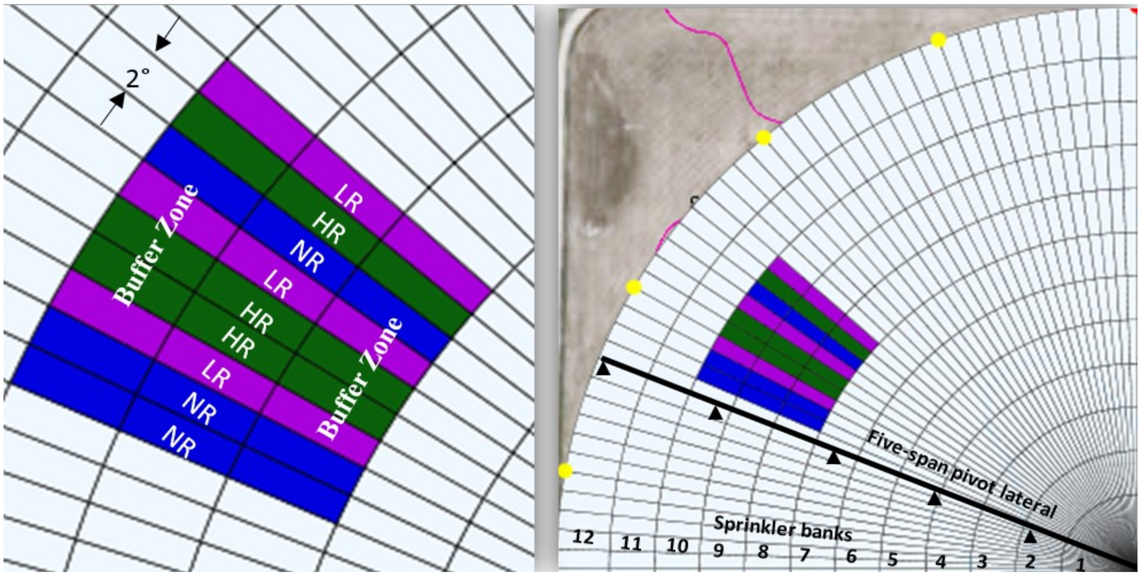


Figure 3.2 Experimental plots location and water application depths for 2013 (HR: high rate, NR: normal rate, LR: low rate)

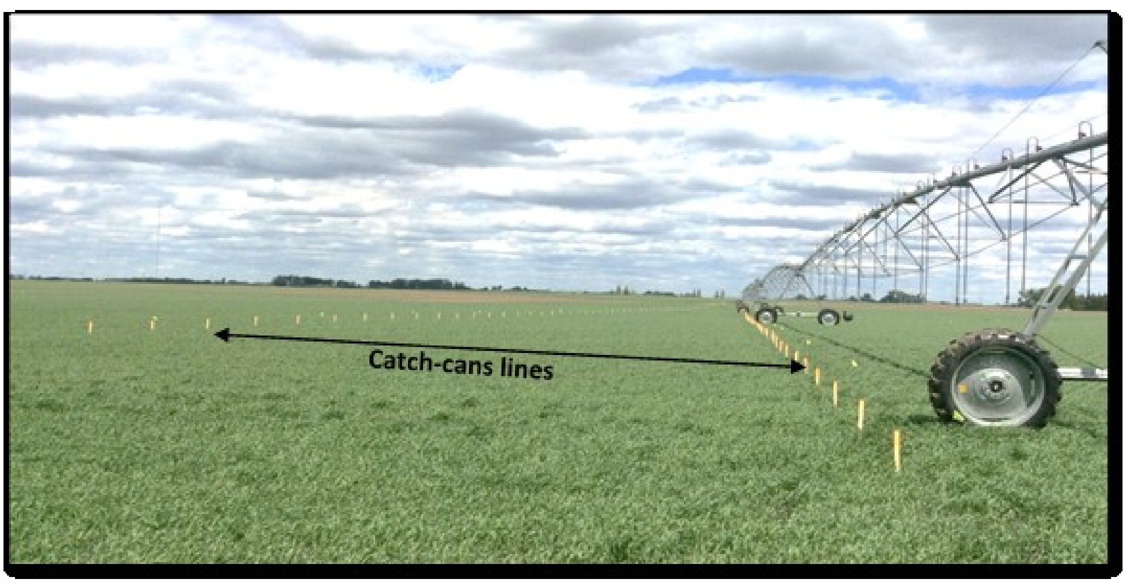


Figure 3.3 Experimental setup for catch-can tests along the pivot lateral (2014)

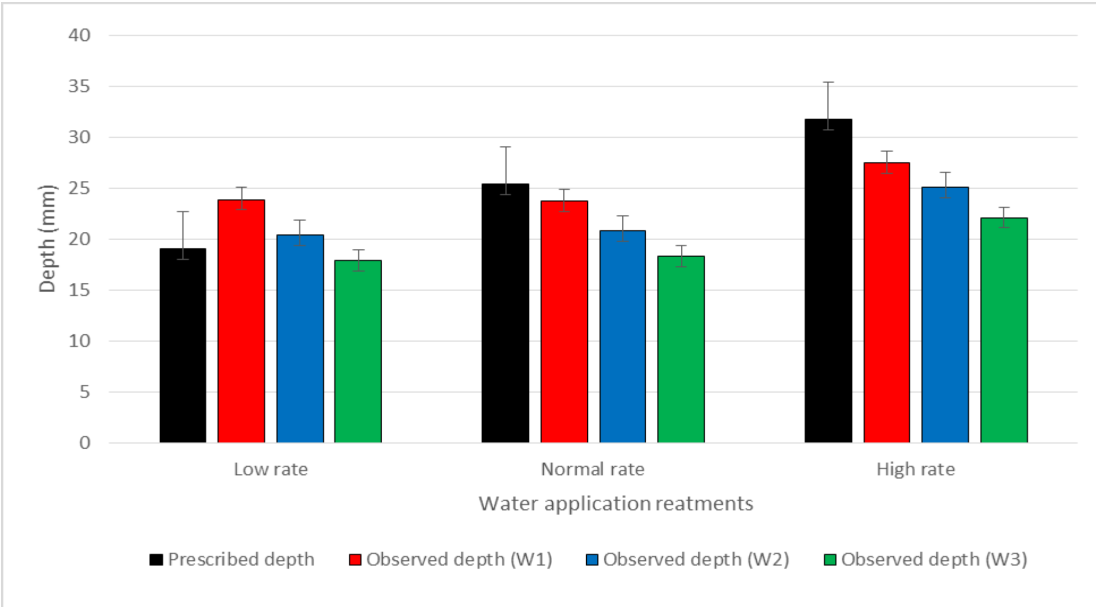


Figure 3.4 The 2013 mean observed and prescribed water application depths (W1: wind speed of 2.4 m s^{-1}, W2: wind speed of 3.3 m s^{-1}, W3: wind speed of 6.5 m s^{-1})

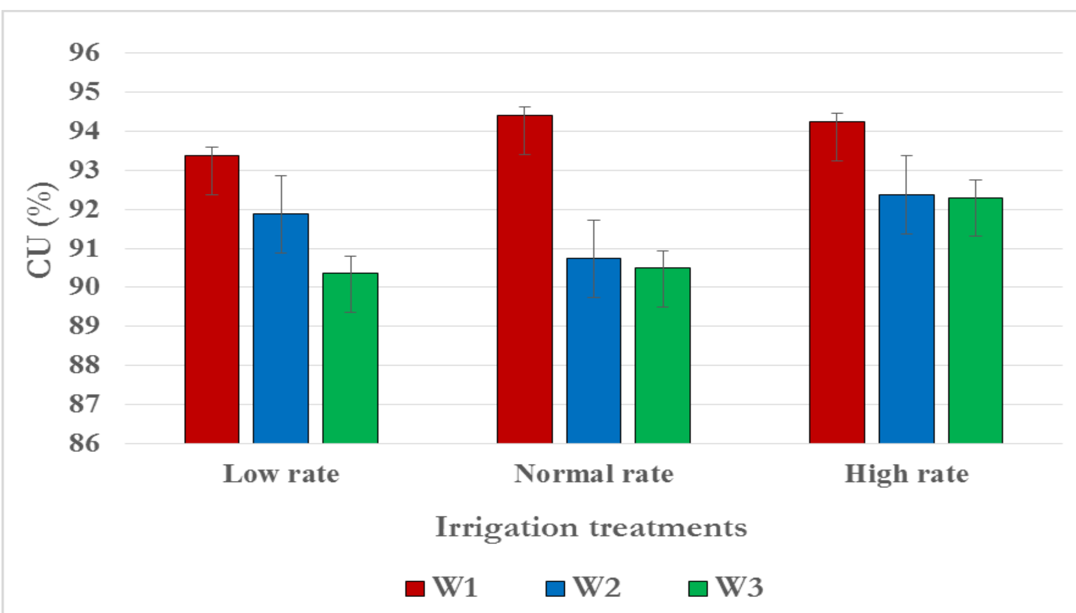


Figure 3.5 Coefficient of uniformity (CU) for three water depths under the three wind speeds (2013) (W1: wind speed of 2.4 m s^{-1}, W2: wind speed of 3.3 m s^{-1}, W3: wind speed of 6.5 m s^{-1})

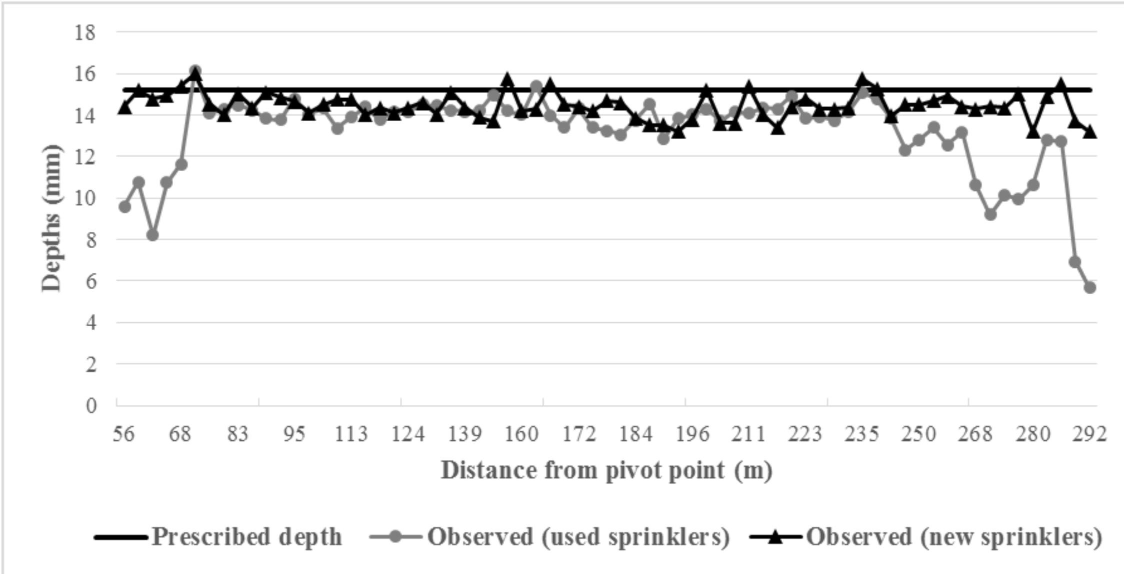


Figure 3.6 The observed and prescribed water depths for constant irrigation

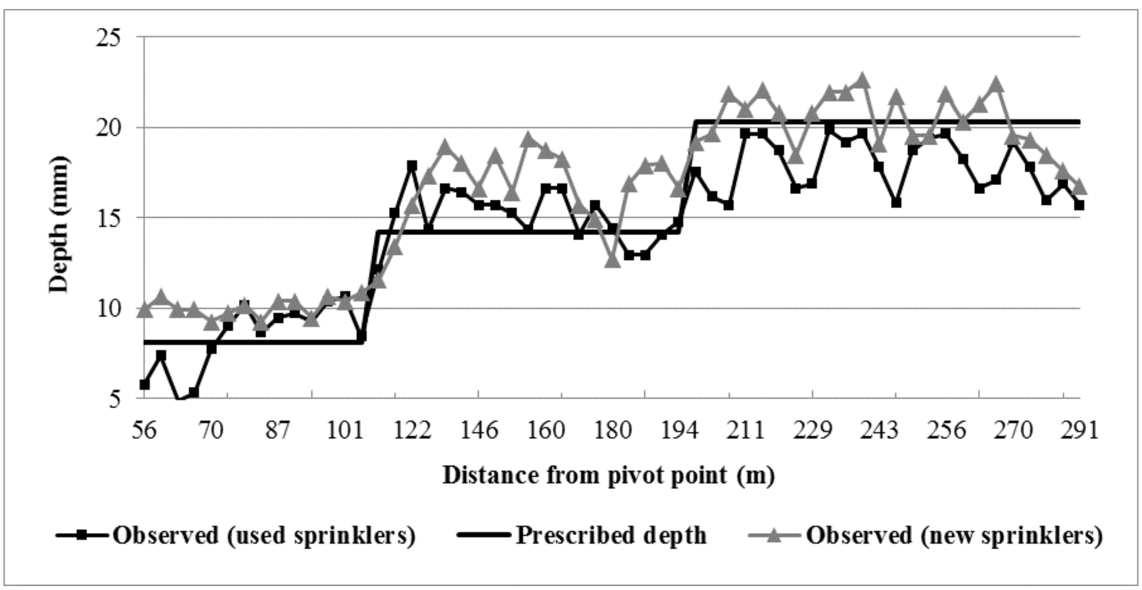


Figure 3.7 The observed and prescribed water depths for variable rate irrigation

Connecting text to Chapter 4

This Chapter is a manuscript accepted for publication in Journal of Irrigation and Drainage Engineering. The manuscript is co-authored by Dr. Chandra A. Madramootoo, Shelley A. Woods, Viacheslav I. Adamchuk, and Hsin-Hui Huang. All literature cited in this chapter is listed in the reference at the end of this thesis.

This chapter covers the assessment of field spatial and temporal variability to delineate site specific management zones for VRI and therefore discusses objective two of this research. As presented in Chapter one, this paper addresses the knowledge gap in the management zones delineation for VRI in southern Alberta. This is the topic of the following article:

“Assessment of Field Spatial and Temporal Variability to Delineate Site-specific Management Zones for Variable-Rate Irrigation”

Contributions made by the different authors are as follows;

1. Aghil Yari, Ph.D. Candidate, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
2. Chandra A. Madramootoo, the thesis supervisor, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
3. Shelley A. Woods, Irrigation and Farm Water Division, Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada.
4. Viacheslav I. Adamchuk, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.

5. Hsin-Hui Huang, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.

The principal author was responsible for preparing the experimental design and methodology, conducting the field work, analyzing data, and the documentation. Prof. Chandra A. Madramootoo, is the thesis supervisor who provided suggestions and proofreading of the manuscript. Dr. Shelley A. Woods provided the extensive technical assistant for conducting the field experiments. She also provided suggestions and proofreading of the manuscript. Dr. Viacheslav I. Adamchuk provided the technical suggestions and proofreading of the manuscript. Mrs Hsin-Hui Huang provided the technical assistant in analyzing the field data.

Chapter 4

Assessment of Field Spatial and Temporal Variability to Delineate Site-specific Management Zones for Variable-Rate Irrigation

Aghil Yari[1], Chandra A Madramootoo[1], Shelley A Woods[2], Viacheslav I. Adamchuk[1], Hsin-Hui Huang[1]

[1] Department of Bioresource Engineering, McGill University, Ste-Anne-de-Bellevue, Quebec, Canada.

[2] Irrigation and Farm Water Division, Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada.

Abstract

Quantification and analysis of field variability are important initial steps in delineating potential variable rate irrigation (VRI) management zones within an agricultural field. This study seeks to utilize variability in soil physical and chemical properties, and field elevation across a 27 ha field at the Alberta Irrigation Technology Centre (AITC) in southern Alberta, Canada, to define site-specific management zones. All geospatial data were collected during the 2013 and 2014 growing seasons. A stepwise multivariate regression approach was used to investigate how multiple measured parameters affect wheat yield. An unsupervised clustering algorithm, fuzzy C-mean, was used to delineate the irrigation management zones. Fuzziness performance index (FPI) and normalized classification entropy (NCE) were used as verification criteria to determine the optimal number of management zones. Results revealed that soil electrical conductivity (EC) and field elevation were better suited for management zone delineation. Three management zones were identified based on the verification criteria using EC and field elevation variables. Measured crop yield differences corresponding to the three non-contiguous management zones were significant.

The study area was categorized as low, medium, and high productive zones. The maximum wheat yield (4.80 t ha^{-1}) was attained in the high productive zone and the lowest (2.22 t ha^{-1}) in the low productive zone.

Keywords: Soil heterogeneity, management zones, center pivot irrigation system, data clustering, field mapping, and southern Alberta.

4.1 Introduction

Alberta accounts for over 75% of the irrigated area in Canada (Alberta Water Council, 2007) and the irrigation industry is the major consumer of fresh water in southern Alberta. About 70% of the irrigated land in southern Alberta is irrigated with a center-pivot irrigation system (CPIS) (Alberta Agriculture and Forestry, 2014). Alberta's irrigation sector, under its *Water for Life Strategy,* is committed to improving water and energy use efficiency and crop productivity by 15% through conversion or modification of existing irrigation systems to low-pressure CPIS (Alberta Water Council, 2007; AECOM, 2009; Alberta Irrigation Projects Association, 2010). Adoption of variable rate irrigation (VRI) in southern Alberta is expected to improve water application taking into account field variability, and increased water use efficiency, crop productivity, and profitability.

Li et al. (2008) noted that the current trend is to implement the site-specific management strategy, rather than the whole field approach, to overcome field variability. For VRI, defining site-specific management zones (SSMZ) is a challenging process due to a complex combination of spatial and temporal variability that affect crop yield (Fridgen et al., 2004). Topographic attributes and apparent soil electrical conductivity (EC_a) are indicators of plant-available water and are effective parameters in management zone delineation (Fridgen et al., 2000). For example, elevation differences across a field can cause water ponding with movement of water from high-elevation areas towards low-elevation areas (Sadler et al., 2000). Kachanoski et al. (1988) reported a strong relationship between soil water content and EC_a. The nature of this relationship varies by location and time.

Topographic attributes and EC_a are the most widely used variables for SSMZ delineation (Fridgen et al., 2000). Fridgen et al. (2004) used EC_a, elevation, and field slope to identify SSMZ using an unsupervised clustering algorithm. The Management Zone Analyst (MZA) software with a fuzzy C-mean clustering algorithm (Fridgen et al., 2004) was used to cluster data into different groups. The optimal number of clusters was selected using verification criteria; fuzziness performance index (FPI) and normalized classification entropy (NCE) index. FPI represents least membership sharing and NCE represents the amount of disorganization of a fuzzy C-partition. Boluwade et al. (2016) investigated a fuzzy C-means algorithm and regionalization with a constrained clustering and partitioning (REDCAP) technique for delineating SSMZ using EC_a and elevation maps. The study found that the fuzzy C-means algorithm using MZA software generated a cost effective solution for delineating SSMZ. Pelcat et al. (2004) employed the fuzzy C-means clustering algorithm using satellite imagery, and this offered the best potential SSMZ in terms of cost. A web-based decision support tool (Zone MAP, NDSU, Fargo, North Dakota, USA) developed (Zhang et al., 2010) to determine the optimal number of zones using remotely sensed images and field data. The SSMZs developed using Zone MAP were consistent with management zones delineated using traditional means.

Spatial and temporal field variability results in uneven distribution of soil water content (Xiang et al., 2007). Uneven field elevation can result in dry zones in high elevation areas and ponding in lower elevation zones. The SSMZs can be created taking soil and topographic variations into account in order to define areas of a field with similar water requirements (Xiang et al., 2007). Redulla et al, (2002) assessed the effects of spatial variability of pH, nutrient availability, and soil texture on four potato fields. They identified that soil texture had the strongest correlation with yield. Crop yield data and related indices such as normalized difference vegetation index (NDVI) can be used in combination with soil chemical and physical characteristics to define SSMZ (Li et al., 2008). Farmer-defined management zones were investigated for variable rate application (VRA) based on farmer's past management experiences, topography, soil color, and aerial images in Colorado (Fleming et al., 2000). The results indicated that the farmer-developed management zones can also be considered as an effective strategy in conjunction with ground assessment (Fleming et al., 2000). Fleming et al. (2004) developed management zones for VRA based on soil color and farmer experience, and compared these with management zones developed using EC_a. Their work indicated that both methods were effective in terms of identifying homogeneous sub-regions but, EC_a was more effective in delineating distinct management zones. Hornung et al. (2006) found that including more data layers to the SSMZ delineation process does not necessarily guarantee the accuracy of the technique. These studies verified that the method with fewer information layers was as precise as the method with more data layers. Optimal choice of the most effective variables to management zone delineation models minimizes the costs associated with data collection, and maximizes the effectiveness of prescription maps.

The overall goal of this study was to develop SSMZ within a field irrigated with a CPIS and retrofitted with a commercial VRI package. Specific objectives of this study were, 1) to investigate a stepwise multivariate regression approach to identify optimum number of variables for management zone delineation, 2) to delineate potential management zones using a fuzzy C-mean clustering algorithm based on the most influential and effective parameters, and 3) to verify the delineated management zones with measured crop yield.

4.2 Materials and methods

4.2.1 Study area and irrigation system

The experimental site was a 27 ha circular field irrigated with a five-span CPIS at the Alberta Irrigation Technology Centre (AITC). The AITC is located in southern Alberta at latitude 49.69º N and longitude 112.74º W with a mean elevation of 905 m above mean sea level. The experimental field was situated within the St. Mary River Irrigation District (SMRID), east of the city of Lethbridge (Fig. 4.1). The SMRID irrigation district comprises 137,000 ha irrigated area and its irrigation water is taken from the St. Mary River (Alberta Agriculture and Forestry, 2014). Average maximum and minimum growing season temperatures in Lethbridge were 21 °C and 6 °C, respectively, over the period from 2000 to 2015 (Alberta Agriculture and Forestry, 2015a). The mean annual precipitation was 384 mm and varied from 207 to 747 mm over the period 1971 - 2015 (Alberta Agriculture and Forestry, 2015a).

A five-span CPIS with a lateral length of 294 m retrofitted with a commercial VRI (Valmont Industries, Inc., Valley, Nebraska, USA) was used to irrigate the experimental site. The system was equipped with Nelson rotator sprinkler nozzles (R3000, D6-Red) and 1.2 bar pressure regulators (Nelson Irrigation, Inc., Walla Walla, Washington, USA). The sprinkler package (low elevation spray application) comprised 129 sprinklers, divided into 12 sprinkler banks. Each sprinkler bank had 10 - 12 sprinklers.

4.2.2 Field elevation

Figure 4.2 illustrates the field elevation map obtained using a real time kinematic (RTK) global navigation satellite system (GNSS) receiver. The area exhibits an elevation ranging from 907 at highest point in the southwest portion of the field and 903 m at lowest point in the east and north portions of the field. In terms of water movement, the highly variable elevation in this field is a critical factor for determining management zones. Excess water in low elevation areas affect plant growth and quality during heavy rainfall due to a lack of a drainage system at approximately 20% of total area. Conversely, in high-elevation areas, water loss due to surface runoff reduces deep penetration of water to the effective plant root zone and, consequently, limits plant growth due to water deficits.

4.2.3 Soil electrical conductivity (EC)

The apparent soil electrical conductivity (EC_a) was measured using an EM38 instrument (Geonics Limited, Mississauga, Ontario, Canada) and Veris® 3100 (Veris Technologies, Inc., Salina, Kansas, USA) in 2013. The data layer collected by the EM38 instrument was included in this manuscript. Soil samples were collected for soil electrical conductivity (EC) measurement, at various points within the EM38 survey area. There was a strong positive relationship between the EC_a and EC for the study area. The relationship was then used to make predictions of EC (dS m^{-1}) from the EC_a (mS m^{-1}) data. High-density geospatial EC maps were produced based on ordinary kriging interpolation, using the commercial GIS package ArcGIS™ (version 10.2.2, ESRI, Redlands, California, USA). The top-right 90º radial sector was not mapped due to on-going farming operations. Maps of elevation (Fig. 4.2) and EC (Fig. 4.3) indicate a strong inverse relationship between EC and elevation (low elevation areas have a greater EC and high elevation areas have lower EC values) in the top-left and bottom-left 90º radial sectors. However, in the most eastern part of the study site, this inverse relationship is not strong. The lateral movement of water and nutrients from high elevation to low elevation areas due to steep land slopes may be the reason for a strong inverse relationship between EC and elevation in the western part of the site. Highly variable elevation created areas of ponded water and the lack of adequate drainage caused higher salinity level in the spots mostly situated in the western part of the study site. However, this is not the case in the most eastern part of the field due to the flatter elevation.

4.2.4 Data collection from experimental plots

In the 2013 growing season, two experimental blocks (Fig. 4.4) were selected for data collection. Block 1 (B1) was situated in high EC and low elevation areas and block 2 (B2) in medium EC and elevation areas. In 2014, another experimental block (block 3, B3) in the low EC and high elevation areas was included. Each block was divided to 9 experimental plots for data collection purposes and each experimental plot had an area of 192 m^2. The mean EC in the 0-90 cm depth ranged between 1.8 to 7.75 dS m^{-1}, 0.5 to 4.1 dS m^{-1}, and 0.37 to 2.6 dS m^{-1} for the experimental plots located in B1, B2, B3, respectively. The elevation ranged between 904 to 904.6 m, 904.6 to 905.2 m, and 905 to 906.1 m for the experimental plots located in B1, B2, B3, respectively.

4.2.4.1 Crop data

In 2013 and 2014, Hard Red Spring (HRS) wheat was sown with seeding rate of 158 kg ha^{-1} in the experimental blocks. In 2013, HRS wheat (Carberry variety) was planted on May 2, and harvested on September 4. In 2014, the same HRS wheat variety was planted on May 15, and harvested on September 18. All experimental blocks were fertilized equally, and fertilizer was applied according to Alberta Agriculture and Forestry recommendation. A total of 218 kg ha^{-1} and 195 kg ha^{-1} of nitrogen (46-0-0) were applied in the 2013 and 2014 growing seasons, respectively. A plot-sized combine (Wintersteiger Ag, Austria) was used to harvest the crop in the experimental plots. Three sampling areas were selected to collect the grain yield in each plot.

4.2.4.2 Soil physical and chemical properties

Georeferenced soil samples were taken from three depths in three locations (0-30, 30-60, and 60-90 cm) in each experimental plot (Fig. 4.5) in 2013 and 2014. A total of 243 soil samples were taken from 81 locations at three different depths and prepared for chemical and physical analyses.

Particle-size analysis (sand, silt, and clay) was performed using the hydrometer with Bouyoucos method (Sheldrick and Wang, 1993). The saturated soil paste was made (1:2 suspension) and the soil pH was determined directly on the paste. Electrical conductivity (EC) of the saturated paste, and solution concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and sodium (Na^{+}) were measured (Janzen, 1993). The amount of Ca^{2+} and Mg^{2+} in the saturated paste extract was determined by Flame Atomic Absorption Spectrometry and Na^{+} and K^{+} by Flame Photometer (Baker and Suhr, 1982). Undisturbed soil samples at the same three sampling depths were taken and soil bulk density was determined. Organic matter in soil was measured by loss on ignition procedure (Goldin, 1987).

4.2.4.3 Irrigation applications

HRS wheat grown under ideal conditions requires 420 to 480 mm of water per growing season in southern Alberta (Alberta Agriculture and Forestry, 2013). Irrigation frequency and depth were recommended by Alberta Agriculture and Forestry using the Alberta Irrigation Management Model (AIMM-version 3.1.3, Alberta Agriculture and Forestry, Calgary, 2010). A total of four irrigations were applied in the 2013 growing season on July 16 and August 19, 21, 27. In 2014, there were six irrigation events on July 9, 11, 28, 29 and August 6 and 8. In a few cases the required irrigation amount was applied on two consecutive irrigation events to prevent surface runoff and to allow for the infiltration of water. The total applied irrigation depth was 81.27 mm and 104.2 mm in 2013 and 2014, respectivley. The mean application uniformity during the irrigation events over the two years was 92% and wind speed ranged between 1.2 m s^{-1} to 6.6 m s^{-1}.

4.2.4.4 Soil water tension

Soil water tension was measured continuously, with five minutes intervals using the Hortau soil tension sensors (Irrolis™ MultiSense Tx3 (#2000) Web Based, Hortau Co., Quebec City, Quebec, Canada) in the experimental plots. The 18 and 27 soil tension sensors were installed to a depth of 30 cm (effective root depth) in 2013 and 2014, respectively and Hortau's TX^3 field monitoring stations were used to send data to a base station (Fig. 4.5).

4.2.5 Statistical analysis

A stepwise multivariate regression model was performed (IBM SPSS Statistics, Version 20.0. Armonk, New York, USA) with forward selection to determine the optimum number of the variables. Analysis of variance (ANOVA) was performed (SAS 9.4, SAS Institute Inc., Cary, North Carolina, USA) to compare the wheat yields differences at the 95% level of probability within three experimental blocks. A Shapiro-Wilk normality test was used to determine whether the data was drawn from a normally distributed population.

4.2.6 Management zone delineation

The fuzzy C-mean clustering technique classifies observations data into C groups of distinct clusters. Three matrices are involved in the clustering procedure and the technique has been described mathematically in the numerous literatures (Bezdek, 1981; Odeh et al.,1992; Fridgen et al., 2004; Li et al., 2008; Boluwade et al., 2016).

4.2.7 Clusters validity functions

To evaluate the performance of the fuzzy C-mean algorithm and delineated management zones, the FPI and NCE were adopted (Bezdek, 1981; Odeh et al., 1992; Boydell and McBratney, 2002). The FPI index is a measure of the degree of separation and ranges from 0 to 1 and the NCE index indicates the amount of disorganization of a fuzzy C-partition and ranges from 0 to 1. As the FPI approaches 0, membership sharing decreases and clusters become more distinct. Conversely, when the FPI approaches 1, membership sharing increases and clusters are less distinct (Fridgen et al., 2000, 2004; Pelcat et al., 2004). The NCE values near 0 indicate greater organization within cluster members and values approaching 1 indicate a higher degree of disorganization.

The MZA software (Management Zone Analyse, version 1.0.1, University of Missouri, Colombia, Missouri, USA) was used to develop SSMZ. The MZA calculates descriptive statistics, performs the unsupervised C-mean fuzzy algorithm, and provides two verification indices (Fridgen et al., 2004) to find the optimum number of management zones. The MZA was performed by setting the clustering parameters based on the recommended values by Odeh et al. (1992) and Fridgen et al. (2004). The Mahalanobis measure of similarity (Odeh et al., 1992; Fridgen et al., 2004) was selected for the clustering procedure (fuzziness exponent = 1.3, maximum number of iterations = 300, convergence criterion = 0.0001, minimum number of zones = 2, and maximum number of zones = 10) and values were determined for the clustering process.

4.3 Results and discussion

4.3.1 Stepwise multivariate regression approach

Descriptive statistics including means, minimum and maximum values, standard error (SE), and standard deviation (SD) for soil physical and chemical properties, elevation, total irrigation during the growing seasons, and average soil water tension during the growing seasons are summarized in Table 4.1.

According to particle-size analysis, soil textures in the depth 0-90 cm, were mostly sandy clay loam (SCL). The average particle size distribution was 52% sand, 24% clay, and 24% silt. The mean organic matter content in the top soil (0-30 cm) was 2.6%. The EC varied widely across the experimental plots and ranged between 0.37 and 7.75 dS m^{-1}. However, as a result of the interpolation, the predicted EC map (Fig. 4.3) from EM38 measurements showed that the EC ranged between 0.79 and 4.9 dS m^{-1} thus masking the underlying high EC variability in the experimental block 1.

A stepwise multivariate regression approach was carried out with ten independent variables and a forward selection approach was conducted separately for the 2013 and 2014 growing seasons. Dependent variables such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} were removed from the input variables due to strong correlation with EC. Pearson's correlations between each variable and the crop yield value are presented in Table 4.2. It was found that elevation and EC were the variables with a strong correlation with the crop yield in both years. There was a largely inverse relation between EC and crop yield with R-Square values of -0.46 and -0.61 in 2013 and 2014, respectively. A positive correlation was found between field elevation and crop yield with R-Square values of -0.47 and -0.52 over the two years. Elevation and EC had the most influence on yield with higher yields observed at higher elevation and lower EC areas. Table 4.3 shows the models resulting from stepwise approach for the 2013 and 2014 growing seasons. A better model was generated between pH and field elevation with crop yield in 2013. In 2014, a better relationship was established between EC and crop yield. These results are in agreement with those obtained by Peralta et al. (2013). Field measurement of all soil physicochemical and field information are not feasible due to limitations of time and cost. Therefore, the easier measurements and inexpensive field information such as EC and field elevation are usually preferred to delineate SSMZ for an irrigated field. There are a handful of parameters for management zone delineation, however the delineated management zone should be accurate, simple, and inexpensive to collect the minimum data requirement. Stepwise analysis of the available variables indicated that EC, pH, and field elevation are the most important parameters to include when performing management zone delineation for VRI in the study area. Furthermore, the relatively higher R-Square values (Table 2) suggest a strong link exist between EC and field elevation with crop yield. Therefore, EC and field elevation could be major variables for delineating site-specific management zones. Moreover, EC and field elevation data sets are becoming easily accessible, allowing for the cost-effective delineation of management zone.

4.3.2 Management zone delineation

The management zone delineation for VRI using an unsupervised clustering algorithm, fuzzy C-mean, has extensively been studied in recent years. The fuzzy C-mean algorithm provides a couple of verification criteria to find the optimum number of management zones. The C-mean clustering technique was used to delineate irrigation management zones using EC and field elevation parameters for the study site. The FPI and NCE were used to identify the optimum number of management zones. The minimum FPI and NCE were observed (Fig. 4.6) for three clusters, which indicates an optimum number of three management zones. A management zone map was produced (Fig. 4.7). The classification of the study site to three management zones follows the EC and elevation patterns of the field. Management Zone one (MZ1) includes the higher EC area with an average EC of 5.35 dS m^{-1} and elevation of 903.5 m. Management Zone two (MZ2) includes the medium EC area with an average EC of 1.39 dS m^{-1} and elevation of 904.9 m. Management Zone three (MZ3) includes the lower EC area with an average EC of 0.74 dS m^{-1} located in the high elevation area with the mean elevation of 904.9 m.

4.3.3 Crop yield analyses for management zones validation

Further analyses were carried out to validate the appropriateness of the management zones using measured grain yield in the 2014 growing season from the experimental blocks located in the delineated management zones (the 2013 data were not shown because only represented two management zones). The statistical analyses identified that the grain yields were significantly ($P<0.05$) different among the three management zones. The crop yield measurement and management zone delineation led us to categorize the study area to three different productive areas namely; low, medium, and high productive areas or MZ1, MZ2, and MZ3, respectively. The highest grain yield (4.80 t ha^{-1}) was produced within MZ3 where the EC value was low and elevation was high. The lowest grain yield was in MZ1 situated in the high EC and low elevation area (Table 4.4). The lower yield in MZ1 can be related to mostly water ponding. The salt tolerance threshold and slope for the wheat grain yield are 5.9 dS m^{-1} and 3.8% (Wallender and Tanji, 2011), respectively. The wheat is rated as tolerant to salinity but salinity higher than 5.9 dS m^{-1} can negatively impact the wheat yield. The average EC were 5.35, 1.55, and 0.74 dS m^{-1} for MZ1, MZ2, and MZ3, respectively and the crop yield was mostly lower in MZ1 due to a combination of water ponding and salt accumulation over the growing season. It can be seen from Table 4.3, soil physical properties were not the main driver of field variability in the study site but the soil EC is significantly different within the management zones. Salt accumulation due to seepage at low elevation areas, resulted in low crop yields at several locations within the study site. Water moves laterally from high elevation to low elevation area due to over-irrigation or heavy rainfall and eventually creates water-logged areas at low elevation areas during the wet years. Lack of a drainage system in this study site exacerbated the impact of salinity to crop growth in low elevation areas.

4.4 Conclusions

The suitability of a stepwise multivariate regression approach in conjunction with a fuzzy C-mean clustering technique to create the optimum number of management zones based on limited variables was assessed at the study site. The study found that a stepwise multivariate regression approach can be used to determine the most appropriate variables for a management zone delineation. Soil EC, pH, and field elevation were the most effective parameters for management zone delineation. Since, soil EC and elevation can be obtained with on-the-go soil sensing technology at a relatively low cost, it is more effective to delineate irrigation management zones based on the EC and field elevation for VRI at the study site.

A fuzzy C-mean unsupervised clustering technique was successfully used to develop management zones based on the soil EC and field elevation. The FPI and NCE validity criteria identified that the three management zones were the optimum number for the study area. Statistical analysis showed that the delineated management zones were significantly different in terms of crop yield as well. The study area was categorized as low (MZ1), medium (MZ2), and high productive (MZ3) areas that can be managed individually in terms of agricultural input application. The highest wheat yield (4.80 t ha^{-1}) was obtained in areas where the EC was low (0.74 dS m^{-1}) and elevation was high (906 m). The lowest wheat yield (2.22 t ha^{-1}) was attained in the low productive zone, situated in the high EC (5.35 dS m^{-1}) and low elevation (903.5 m) areas.

4.5 Acknowledgment

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for financial support and they would like to extend their appreciation to the Alberta Irrigation Technology Center for providing equipment and extensive in-kind support. The authors are also grateful to Jim Parker, Alberta Agricultural and Forestry, and Jeff Bronsch, Sunrise AG Company, for providing the soil apparent electrical conductivity and field elevation data.

Table 4.1 Descriptive statistics of measured parameters of experimental site

Variables	Mean	Min.	Max.	SD
pH	7.77	7.53	7.97	0.10
EC (dS m^{-1})	2.6	0.37	7.75	2.34
I (mm-2013)	90.34	80.60	106.40	7.36
I (mm-2014)	102.01	50.41	143.75	24.04
ST (kPa- 2013)	8.34	0.29	16.11	5.56
ST (kPa-2014)	10.83	3.50	21.98	5.20
OM (%)	2.59	2.10	3.10	0.21
Sand (%)	51.78	42.00	58.33	4.86
Clay (%)	24.23	21.00	30.67	2.57
Silt (%)	23.99	18.00	30.33	2.90
BD (g cm^{-3})	1.63	1.40	1.90	0.18
Elevation (m)	905.00	903.00	907.00	0.34

Irrigation (I); Soil tension (ST); Organic matter (OM); Bulk density (BD), Standard deviation (SD)

Table 4.2 Pearson's correlation matrix for all variables measured in the experimental plots

Irrigation (I); Soil tension (ST); Organic matter (OM); Bulk density (BD)

	PH	EC	I 2013	I 2014	ST 2013	ST 2014	OM	Sand	Clay	Silt	BD	Elevation
PH	1.00											
EC	-0.01	1.00										
I 2013	0.05	0.04	1.00									
I 2014	0.07	0.03	0.69	1.00								
ST 2013	-0.48	-0.49	-0.16	-0.45	1.00							
ST 2014	-0.23	-0.07	-0.56	-0.65	0.71	1.00						
OM	-0.42	-0.25	-0.20	-0.20	0.62	0.33	1.00					
Sand	0.54	-0.18	0.14	0.16	-0.39	-0.35	-0.47	1.00				
Clay	-0.41	0.21	-0.20	-0.24	0.34	0.49	0.42	-0.83	1.00			
Silt	-0.53	0.14	-0.09	-0.09	0.35	0.22	0.43	-0.95	0.60	1.00		
BD	-0.03	0.45	0.20	0.25	-0.31	-0.28	-0.12	-0.01	-0.09	0.07	1.00	
Elevation	-0.14	-0.67	0.08	0.13	0.68	0.17	0.24	0.05	0.04	-0.10	-0.19	1.00
Yield 2013	**0.28**	**-0.46**	0.18	0.05	0.15	-0.18	0.29	0.02	-0.05	0.00	-0.11	**0.47**
Yield 2014	-0.17	**-0.61**	-0.04	0.08	0.16	-0.11	0.32	-0.06	-0.03	0.10	-0.18	**0.52**

Table 4.3 Stepwise models for the 2013 and 2014 growing seasons

Year	Selected variables	Model	R-Square	P-value
2013	Elevation	Yield = 0.62 (Elevation) -558.25	0.22	0.005*
	Elevation and pH	Yield = 0.69(Elevation) + 1.02pH - 628.71	0.34	0.002*
2014	EC	Yield = 4.62 – 0.174EC	0.38	0.0001*

* Significant ($p<0.05$)

Table 4.4 The mean soil physicochemical properties at soil depth 0-90 cm and grain yield within the experimental plots located in the three management zones in 2014

Zones	Sand (%)	Clay (%)	Silt (%)	pH	OM (%)	EC (dS m^{-1})	ρ_b g m^{-3}	Y 2014 (t ha^{-1})	Level	P-values
MZ1	50.2	25.4	24.4	7.74	2.57	5.35	1.79	2.22	MZ1 vs MZ2	0.0001*
MZ2	52.9	23.3	23.8	7.80	2.61	1.39	1.55	4.28	MZ1 vs MZ3	0.0001*
MZ3	53.3	23.4	23.3	7.76	2.59	0.74	1.58	4.80	MZ2 vs MZ3	0.004*

Organic matter (OM), Electrical conductivity (EC), Bulk density (ρ_b), Crop grain yield in 2014 (Y 2014)

* Significant ($p<0.05$)

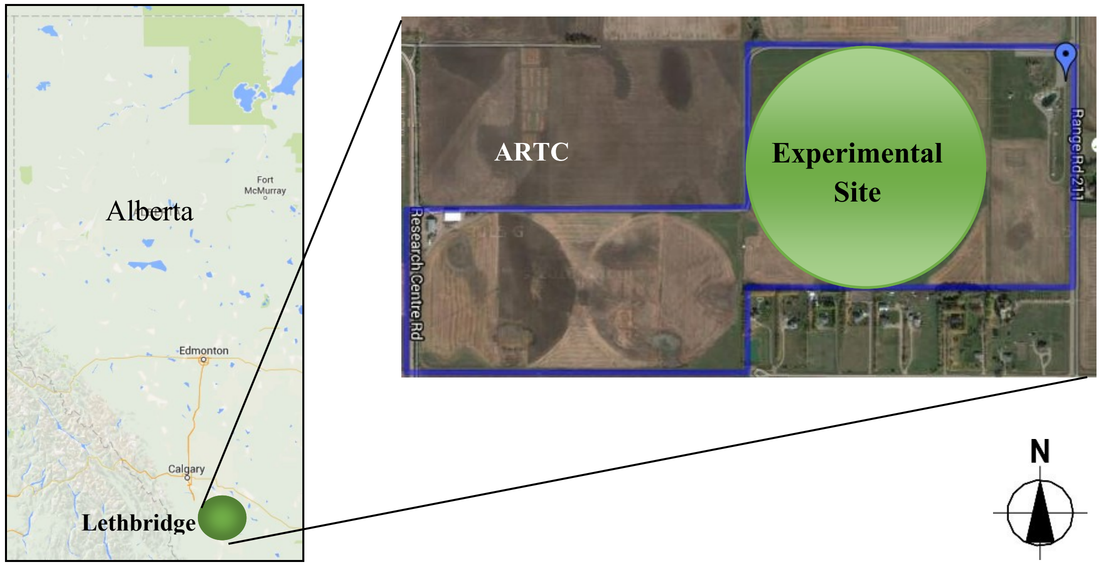


Figure 4.1 Experimental site location in southern Alberta

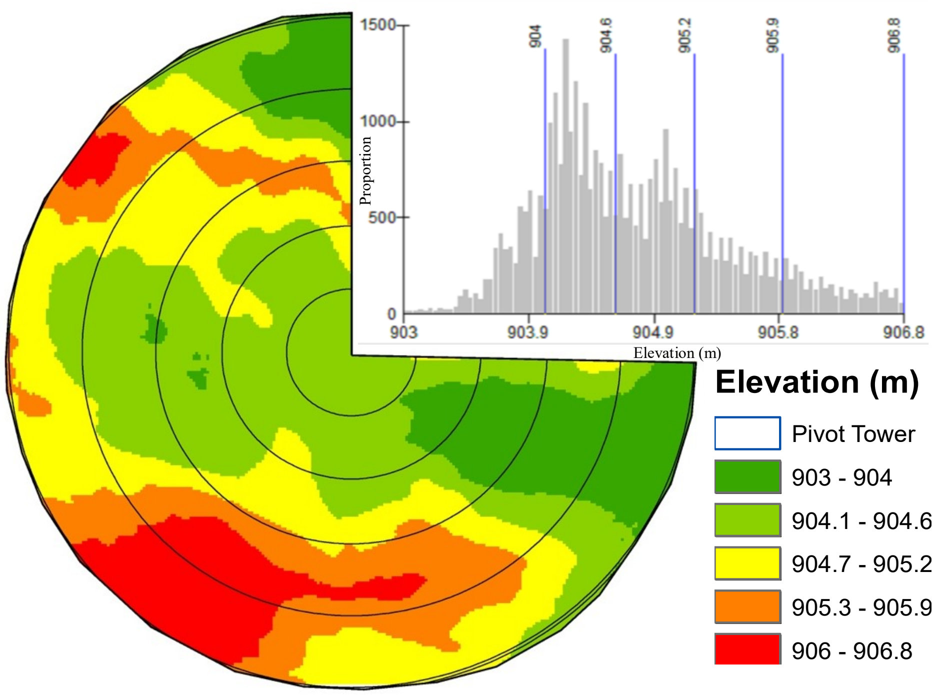


Figure 4.2 Field elevation map and distribution histogram

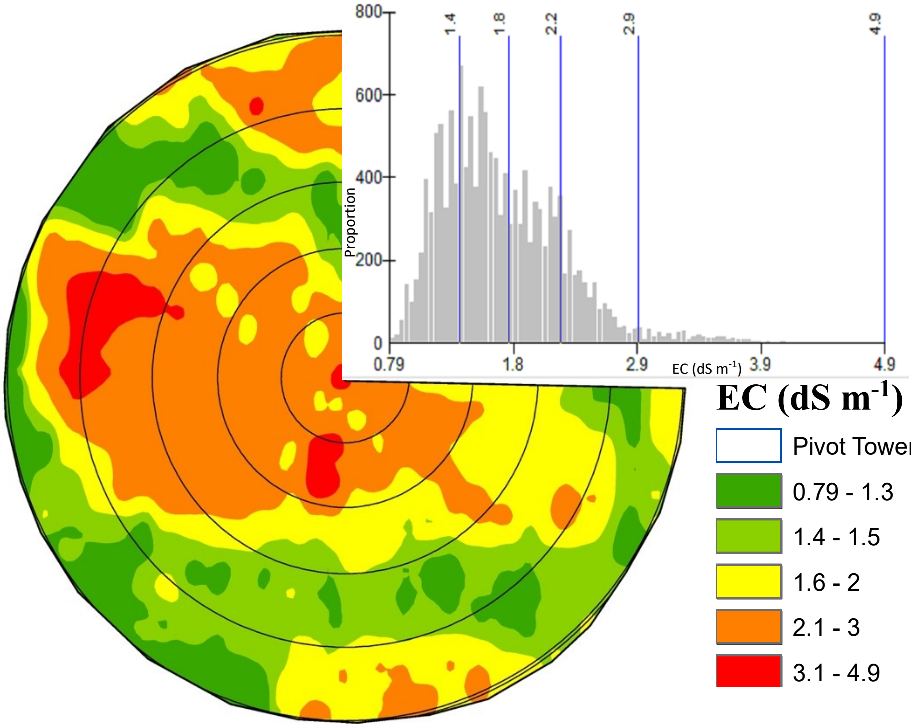


Figure 4.3 Soil electrical conductivity map and distribution histogram

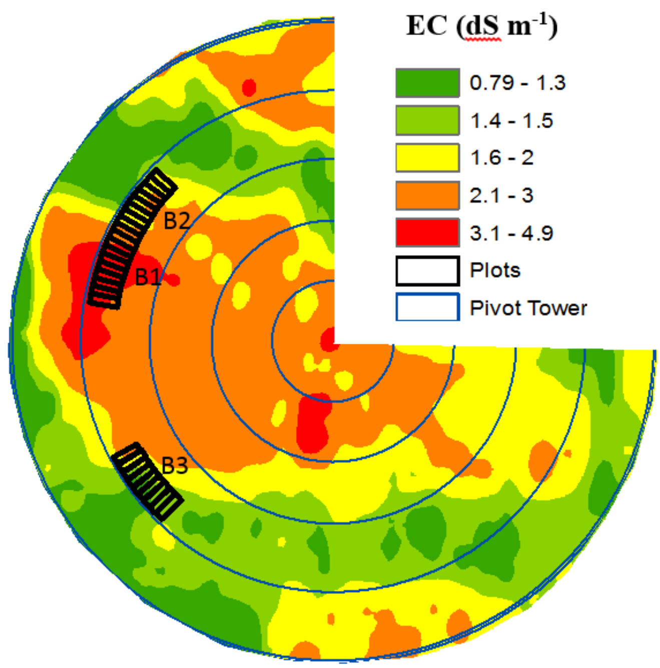


Figure 4.4 Overlay of experimental blocks on EC map (B1, B2, and B3 represents high, medium, and low EC areas, respectively)

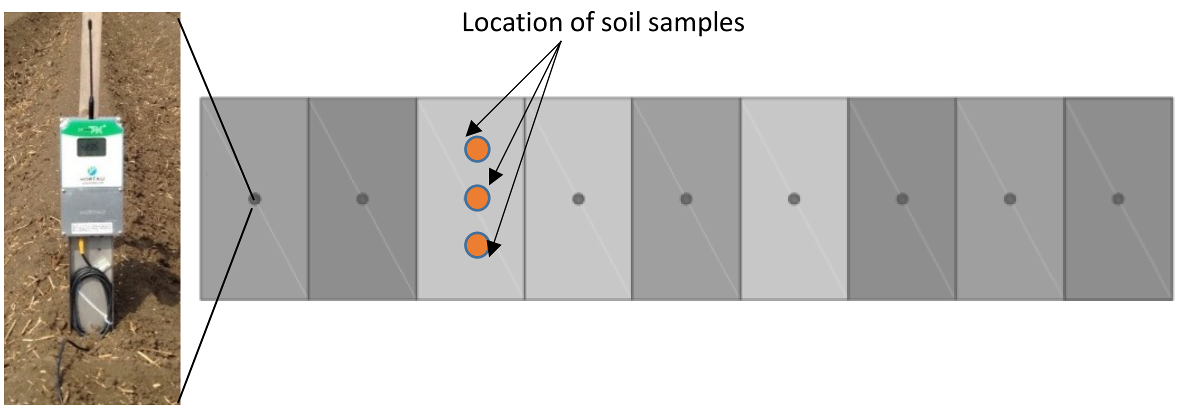


Figure 4.5 Soil tension sensors and soil samples locations within the experimental plots

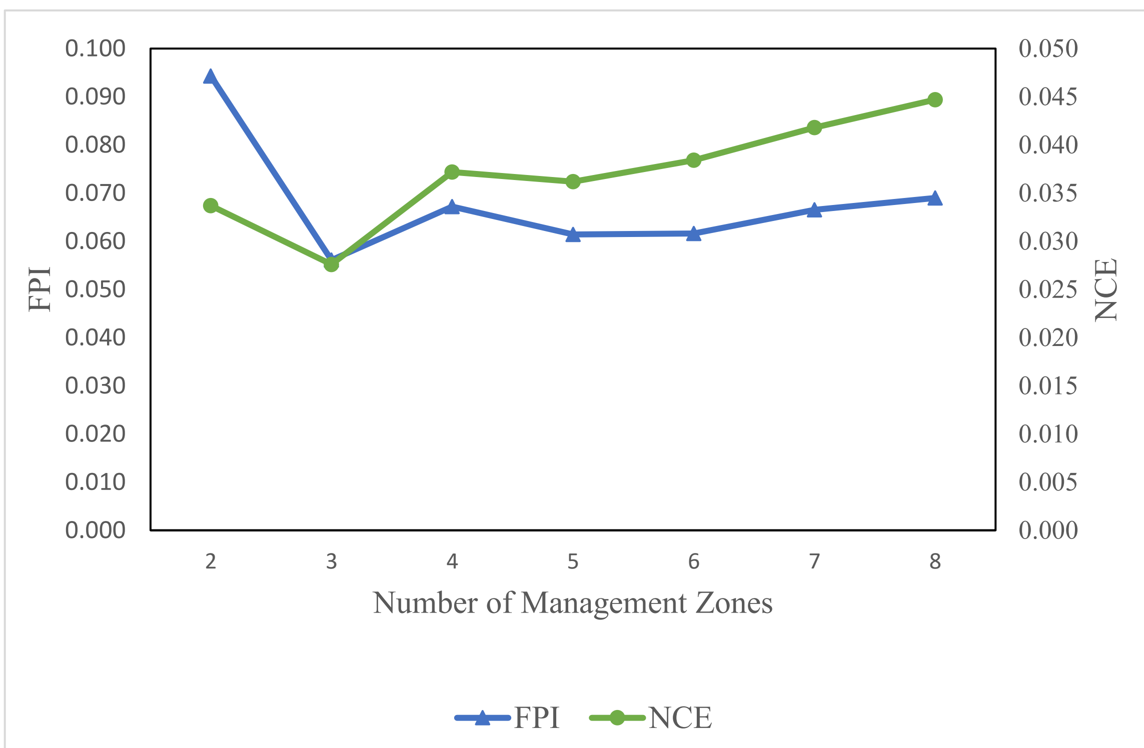


Figure 4.6 FPI and NCE for the experimental site (FPI: fuzziness performance index and represents least membership sharing, NCE: normalized classification entropy index and represents the amount of disorganization of a fuzzy C-partition)

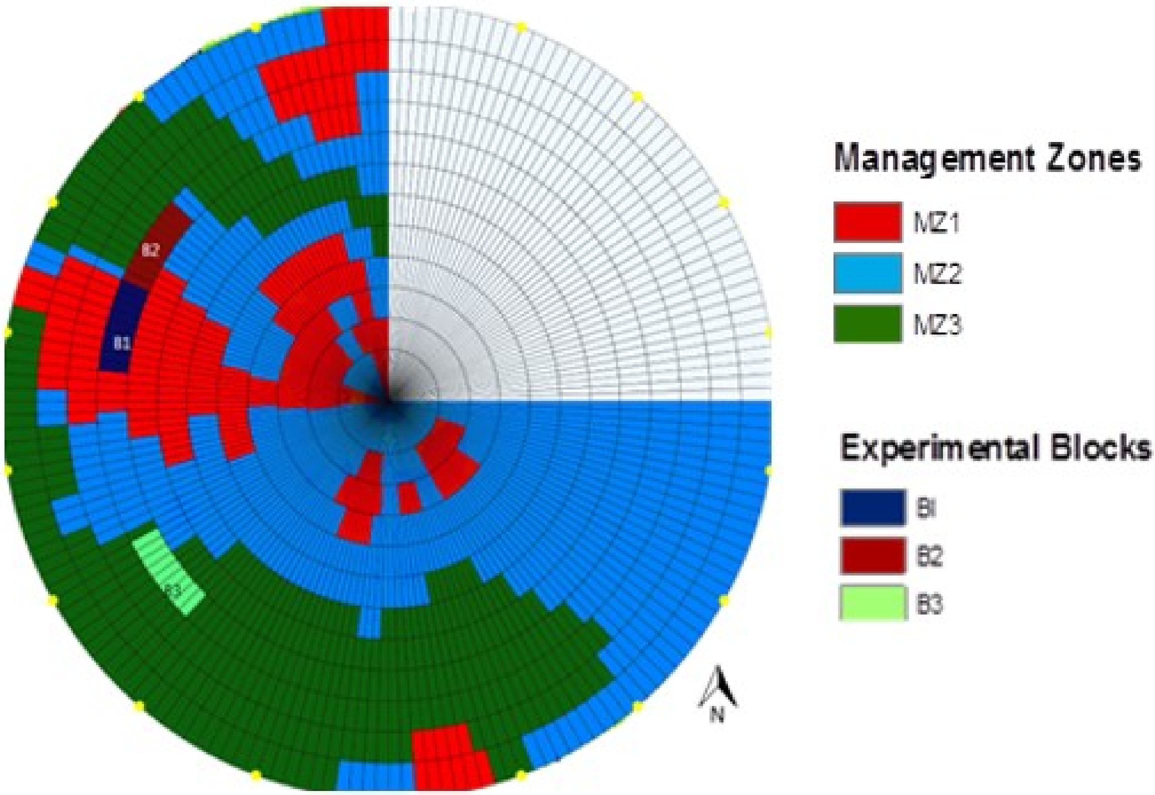


Figure 4.7 Three potential management zones for experimental site produced by Variable Rate Prescription Software (version 6.5, Valmont Industries Inc., Omaha, Nebraska, USA)

Connecting text to Chapter 5

This Chapter is a manuscript submitted for publication in Journal of Precision Agriculture. The manuscript is co-authored by Dr. Chandra A. Madramootoo, Shelley A. Woods, and Viacheslav I. Adamchuk. All literature cited in this chapter is listed in the reference at the end of this thesis.

Chapter five covers an assessment of water and energy consumption and crop productivity of variable-rate irrigation in southern Alberta and therefore discusses objective three of this research. As presented in Chapter one, this paper addresses the knowledge gap in the potential benefits of VRI technology. This is the topic of the following article.

"An Assessment of Water and Energy Consumption and Crop Productivity of Variable-Rate Irrigation; A case study in southern Alberta, Canada"

Contributions made by the different authors are as follows;

1. Aghil Yari, Ph.D. candidate, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
2. Chandra A. Madramootoo, the thesis supervisor, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
3. Shelley A. Woods, Irrigation and Farm Water Division, Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada.
4. Viacheslav I. Adamchuk, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.

The principal author was responsible for preparing the experimental design and methodology, conducting the field work, analyzing data, and the documentation. Prof. Chandra A. Madramootoo, is the thesis supervisor who provided suggestions and proofreading of the manuscript. Dr. Shelley

A. Woods provided the extensive technical assistant for conducting the field experiments. She also provided suggestions and proofreading of the manuscript. Dr. Viacheslav I. Adamchuk provided the technical suggestions and proofreading of the manuscript.

Chapter 5

An Assessment of Water and Energy Consumption and Crop Productivity of Variable-Rate Irrigation; A case study in southern Alberta, Canada.

Aghil Yari[1], Chandra A Madramootoo[2], Shelley A Woods[3], Viacheslav I. Adamchuk[4]

[1, 2, 4] Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada

[3] Irrigation and Farm Water Division, Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada

Abstract

Globally, the irrigation sector consumes approximately 70% of all annual fresh water withdrawals. Improving irrigation efficiency can be largely effective towards water conservation, and increased crop productivity. Excessive irrigation causes waterlogging, salinity, soil erosion, poor crop quality, plant diseases, and environmental degradation. Variable-rate irrigation (VRI) technology customises irrigation water applications to meet site-specific needs. Therefore, improving irrigation efficiency by adoption of VRI can be an effective method to save water and energy, and consequently improve overall productivity. To evaluate water and energy savings consumtion, a two-year field experiment was performed under a center pivot irrigation system retrofitted with a commercial VRI during the 2013 and 2014 growing seasons (May to August) at the Alberta Irrigation Technology Centre (AITC) in southern Alberta, Canada. The results provided important insights into the potential benefits of VRI. Water application under VRI dropped by 25% and 34% during the 2013 and 2014 growing seasons, respectively due to non-application of water to areas such as ponds, roads, and non-cropped areas in the study site. Conventional irrigation systems are designed for uniform water application and do not account for field spatial and temporal variability. In addition, 15.6% and 21.3% reduction in irrigation pumping costs was achieved in 2013 and 2014, respectively. Wheat grain yields were measured under the low, normal and high irrigation treatments. In 2013 growing season, crop yield in high irrigation treatment was significantly higher than the normal irrigation treatment, and no significant reduction in crop yield was found in low irrigation treatment as compared to normal irrigation treatment. In 2014, there were no significant crop yield differences between the irrigation treatments due to significant amounts of rainfall which occurred during the 2014 growing season.

The FAO AquaCrop model was used to simulate the potential crop yield production under different management zones and various irrigation scenarios in the study site. The model indicated that, the more irrigation in the crop development stage can contribute on significant crop yield improvement.

Keywords: Variable-rate irrigation, water and energy savings, water conservation, center pivot irrigation system, excessive irrigation, crop yield, and crop model.

5.1 Introduction

Low-pressure center-pivot irrigation systems (CPIS) are the most developed irrigation systems in southern Alberta and majority of the irrigators (Alberta Agriculture and Forestry, 2014) have been using the CPIS for supplemental and full irrigation. Recent developments in precision irrigation have highlighted the need for variable rate irrigation (VRI) technology to optimise water and energy consumption and improve overall field productivity. Converting or modifying existing irrigation systems to apply water variably would benefit the irrigation industry in southern Alberta.

In light of recent development in VRI technology, there has been an increasing interest to evaluate performance of the technology (Gossel et al., 2013; Chávez et al., 2010; Evans et al., 2013; King et al., 2009; O'Shaughnessy et al., 2013; Stone et al., 2015; Sui and Fisher, 2015). A few studies have attempted to investigate the potential benefits of the VRI technology. Results from studies of VRI indicated that water savings of up to 50% can be achieved in individual year and average water savings over a number of years ranged from 8 to 20% (Sadler et al., 2005; Smith et al., 2010; Charles and Chad, 2014). The VRI systems have the potential to conserve limited water resources by applying the irrigation water based on site-specific needs. These water savings become more important as other sectors compete with agriculture for limited freshwater supplies (Stone et al., 2010). Yule and Hedley, (2008) investigated the water and energy saving benefits of VRI on 22 ha farm in New Zealand. The optimum amount of irrigation was applied within the three management zones and water saving of 20% to 25% was achieved and irrigation operating costs dropped by $77-$113 per hectare. The authors pointed out that the impact of VRI on water and energy savings is very site-specific and adequate information is needed for achieving the full potential of VRI technology.

Optimal irrigation management strategies were implemented on three farms in Oregon, Washington, and Idaho within the Columbia Basin, USA, using VRI technology (Charles and Chad, 2014). Deficit irrigation and spatial optimization of water application approaches were employed to improve farms profitability. Results from the study showed water saving ranged from 4% to 8.8% from the four different irrigation prescription maps during the 2013 growing season (Charles and Chad, 2014).

In addition to water and energy savings, VRI technology has the potential to increase economic benefits by reducing input costs and increasing yields (Smith et al., 2010). LaRue (2011) reported the benefits of a commercial CPIS equipped with the variable rate zone control package (Valmont Industries Inc, Omaha, Nebraska, USA). Overall, 12% less irrigation was applied, and a reduction of 15% in nitrogen was reported. McClymont et al. (2012) investigated the effects of site-specific irrigation management on grapevine yield. The site-specific irrigation management strategy improved water use efficiency and crop yields in low-production areas. There is a little detailed and documented investigation of the potential water and energy savings and crop production benefits of VRI technology. This indicates a need to understand the concept of VRI management in field scale.

The purpose of this study was to evaluate water and energy savings and crop yields production benefits of the VRI. Specific objectives were to; 1) assess water applications under VRI and non-VRI systems, 2) evaluate of potential energy savings under VRI, 3) investigate wheat yields produced in three management zones under three irrigation treatments, and 4) Optimize crop yield production using AquaCrop model.

5.2 Materials and methods

5.2.1 Site description

A two-year field experiment was carried out on 27-ha field at the Alberta Irrigation Technology Centre (AITC) located in southern Alberta (latitude 49.69º N and longitude 112.74º W) with a mean elevation of 905 m above sea level. The research site is situated east of the city of Lethbridge within the St. Mary River Irrigation District (SMRID). The climate is a semi-arid, and characterized by warm and windy summer with occasional storms. An average maximum and minimum daily temperatures during the growing season are 21°C and 6°C, respectively. The mean annual precipitation varies from 207 to 747 mm according to data from 1971 to 2015 (Alberta Agriculture and Forestry, 2015a).

5.2.2 Center pivot irrigation system (CPIS) and variable rate irrigation (VRI)

Irrigation was performed using a five-span 294 m CPIS during the 2013 and 2014 growing seasons. The CPIS was fitted with Nelson rotator sprinkler nozzles (R3000, D6-Red) on flexible drop hoses spaced 2.29 m apart and 1.5 m above the ground. Each individual sprinkler was fitted with 1.2 bar pressure regulators (Nelson Irrigation, Walla Walla, Washington, USA). The CPIS was modified for variable rate application using a VRI zone control package from Valmont (Valmont Industries Inc., Omaha, Nebraska, USA).

The pivot lateral (294 m) with 129 sprinklers was divided into 12 sprinkler banks. Each sprinkler bank was designed to have 10-12 sprinklers. For this research project, only span number four was included to irrigate the experimental plots situated under a single sprinkler bank.

5.2.3 Data collection

5.2.3.1Soil physical and chemical properties

The soil at the study site was mostly sandy clay loam (SCL). The average particle size distribution was 52% sand, 24% clay, and 24% silt. The average organic matter content in the top soil (0-30 cm) was 2.6%. The soil electrical conductivity (EC) varied widely across the experimental site and ranged between 0.43 and 7.75 dS m^{-1} in high and low elevation areas, respectively.

5.2.3.2 Crop information

In 2013 and 2014, the experimental site was seeded to hard red spring (HRS) wheat (Carberry variety) with seeding rate of 158 kg ha^{-1}. In 2013, field preparation and seeding carried out in early

May and harvested on September 4. In 2014, the same HRS wheat variety was seeded on May 15, and harvested on September 18. The experimental site was fertilized and a total of 218 kg ha^{-1} and 195 kg ha^{-1} of nitrogen (46-0-0) were applied in the 2013 and 2014 growing seasons, respectively. An experimental plot was about 192 m^2 in size, and a plot-sized combine (Wintersteiger Ag, Austria) harvested the crop. Three sampling points were selected to collect the grain yield in each plot.

5.2.3.3 Irrigation applications

HRS wheat requires 420 to 480 mm of water per growing season in southern Alberta (Alberta Agriculture and Forestry, 2013). Irrigation frequency and depth were recommended by Alberta Agriculture and Forestry using the Alberta Irrigation Management Model (AIMM-version 3.1.3, Alberta Agriculture and Forestry, Calgary, 2010) during the two-year study in the experimental site. A total of four and six irrigation events were performed in the 2013 and 2014 growing seasons. The total irrigation depths were 81.27 mm and 104.2 mm in the 2013 and 2014 growing seasons, respectively.

5.2.3.4 Soil water tension

Soil water tension was recorded continuously every 5 minutes for the top soil in depth 0-30 cm using the Hortau (MultiSense Tx3-Web Based) soil tension sensor (Hortau Co., Quebec, Canada) in all experimental plots. The 18 and 27 soil tension sensors were placed to a depth of 30 cm in 2013 and 2014, respectively. The Hortau Tx3 field monitoring station was installed in the experimental plots and had three ports to accommodate a soil temperature sensor and a tensiometers. The Tx3 was powered by 1.5 V “C” size batteries and wirelessly transmitted data from the experimental plots to the Hortau Web Base Station which was installed in the experimental site in approximately 400 m from the experimental plots. The Web Based Station was powered by 10 W solar energy panel with a 12 V battery for storing the excess energy for nights and cloudy days. The Web Based Station received data from the Tx3 and transmitted to the Hortau Web Server. The connection between the Web Base Station and the Web Server was facilitated through cellular networks.

Soil water content for field capacity (FC) and permanent wilting point (PWP) were identified in percent volume using laboratory-determined soil-water retention curves.

5.2.3.5 Water and energy consumption

A flow meter (AG701, Saddle Magmeter, Seametrics Incorporated, Washington, USA) was installed in 2014 at the pivot point of the system to monitor and record water usage during the irrigation events. Water discharge was recorded continuously every minute using data logger and Prolog data logger software (Version 2.3037, Lakewood Systems Ltd., Edmonton, Alberta, Canada) over the 2014 growing season.

Energy consumptions and costs were calculated using the Alberta Irrigation Energy Calculator (Alberta Agriculture and Forestry, 2008) based on the average energy price in 2013 and 2014 growing seasons. Alberta Irrigation Energy Calculator was developed to estimate and compare the cost of energy for irrigation systems operations. The inputs consist of type of irrigation system, irrigated area, system flow rate, pump operating pressure, pump efficiency, average energy cost over the growing season, and seasonal operation hours.

5.2.4 Experimental design and statistical analysis

An optimum number of three management zones was identified for experimental site using apparent soil electrical conductivity (ECa) and filed elevation. Management zone one (MZ1) represents high ECa and low elevation, management zone two (MZ2) represents medium ECa and medium elevation, and management zone three (MZ3) represents low ECa and high elevation. Three experimental blocks were structured within the three management zones. Block 1 (B1) was located within MZ1, Block 2 (B2) in MZ2, and Block 3 (B3) in MZ3 (Figure 5.1).

In the 2013 growing season, three water application depths were applied randomly (randomised complete block design (RCBD)) in three replicates on two pre-defined management zones (MZ1 and MZ2), resulting in 18 plots (Figure 5.2). The dimensions of each experimental plot were 24 m by 8 m. The three water application depths included: normal irrigation (NI), low irrigation (LI), and high irrigation (HI). The NI treatment was a water application depth of 25.4 mm with each irrigation event, the LI was a water application depth of 19.1 mm, and the HI was a water application depth of 31.7 mm. The NI was intended to simulate a typical practice as determined by Alberta Agriculture and Forestry using the Alberta Irrigation Management Model. The LI was meant to simulate under-irrigation and the HI was intended to simulate over-irrigation.

In 2014, another block (B3) was added to the experimental site located in MZ3 in order to cover more area with a wider range of variability. Three irrigation treatments were imposed randomly in three replicates on three management zones, resulting in 27 plots. The three irrigation treatments included three different water depths: NI, LI1, and LI2. The NI treatment was a water application depth of 25 mm, the LI1 was a water applications depth of 17.8 mm, and the LI2 was a water application depth of 10 mm. In 2014, the amount of irrigation depths were changed to lower depths in order to assess an impact of deficit irrigation on crop yields. The NI was intended to simulate a typical practice as determined by Alberta Agriculture and Forestry using the Alberta Irrigation Management Model. The LI1 and LI2 was meant to simulate under-irrigation.

An analysis of variance (ANOVA) was performed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA) to determine whether there are any significant differences between the means of crop yields among the three irrigation treatments and management zones.

5.2.5 Crop yield prediction using AquaCrop model for VRI decision support

The purpose of the study was to ascertain whether simulated crop yields can be added to the decision making process with respect to the delineation of the site specific zones. Based on the soil, crop, and weather data for each management zones, crop yields were simulated under three irrigation treatments using AquaCrop model (Version 4, Land and Water Division, FAO). AquaCrop simulates growth, productivity, and water use of a crop on a daily basis under rain-fed, deficit, and full irrigation condition (Doorenbos and Kassam, 1979). An empirical water production function is used to assess yield response to water:

$$\left(1-\frac{Y}{Y_m}\right)=k_y\left(1-\frac{ET}{ET_m}\right) \tag{5.1}$$

where, Y_m and Y are the maximum and actual yield, ET_c and ET are the maximum and actual evapotranspiration, and k_y is the yield response factor. The Y/Y_m is the relative yield $(1 - Y/Y_m)$ the relative yield decrease, ET/ET_c the relative evapotranspiration and $(1 - ET/ET_c)$ the water stress or relative evapotranspiration deficit.

The AquaCrop inputs consist of climate data, crop information, irrigation management, field management, soil physical and chemical properties, and initial condition for the simulation period. The model uses climate data which consist of daily, 10-day or monthly. Daily maximum and minimum air temperature (ºC), and rainfall (mm day^{-1}), were obtained from weather station of

Alberta Irrigation Technology Center located in the study site (Alberta Agriculture and Forestry, 2015a). The crop, soil, irrigation, and management parameters were recorded during the 2013 and 2014 growing seasons in the experimental site. The model was calibrated and validated by minimizing error between simulated and observed crop yield for the experimental plots.

The FAO Penman-Monteith equation (Allen et al., 1998) was used to calculate reference and crop evapotranspiration:

$$ET_c = K_c \times ET_o \tag{5.2}$$

$$ET_o = \frac{0.408 * \Delta * (R_n - G) + \gamma * \left(\frac{900}{T+273}\right) * u_2 * (e_s - e_a)}{\Delta + \gamma * (1 + 0.34 * u_2)} \tag{5.3}$$

Where

ET_c = Crop evapotranspiration (mm day^{-1})

ET_o = Reference evapotranspiration (mm day^{-1})

K_c = Crop coefficient

R_n = Net radiation at the crop surface (mMJ m^{-2}day^{-1})

G = Soil heat flux density (MJm^{-2}day^{-1})

T = Mean daily air temperature at 2 m height (°C)

u_2 = Wind speed at 2 m height (m s^{-1})

e_s = Saturation vapour pressure (kPa)

e_a = Actual vapour pressure (kPa)

e_s-e_a = Saturation vapour pressure deficit (kPa)

Δ = Vapour pressure curve (kPa °C^{-1})

γ = Psychrometric constant (kPa°C^{-1})

5.3 Results and discussion

5.3.1 Weather condition during the 2013 and 2014 growing seasons

The 2013 and 2014 growing seasons were wet and significant rainfall fell from April to June. The growing season precipitations were calculated from May 1 to September 5 in 2013 and from May 1 to Sep 18 in 2014. The growing season precipitation amounts were 300 mm and 340 mm in 2013 and 2014, respectively. Total growing seasons rainfall during the two experimental years were greater than the long-term average (279 mm). Rainfall was not uniformly distributed throughout the growing seasons and almost 55% of rainfall occurred in June for both growing seasons.

5.3.2 Water and energy consumption

Water applications under variable and constant-rate applications were assessed during the two growing seasons in 2013 and 2014. A management zone map was used to generate four different prescription maps (See Appendix A) during the four irrigation events throughout the 2013 growing season. Water ponding throughout the growing season due to lack of drainage system in the low elevation areas negatively impacted the crop growth. Water consumption during the 2013 growing season under the constant and variable-rate irrigations was calculated based on the prescription maps within four irrigation events. Average water application under the constant and variable-rate irrigation was 90 mm and 67.5 mm throughout the irrigation season, respectively. Overall, 25% less irrigation was applied under the variable-rate irrigation, and a reduction of 15.6% in energy cost was calculated (Table 5.1).

Water consumption during five irrigation events in July and August 2014 under variable and constant-rate irrigations were recorded and are presented in Figure 5.3. Average water discharge under constant and variable-rate applications were about 36.3 and 23.6 l s^{-1} during all the irrigation events, respectively. Five different prescription maps (See Appendix B) were generated throughout the irrigation season and the irrigation events were implemented based on the generated prescription maps. Average water application under the constant and variable rate irrigations was 90 mm and 58.6 mm, respectively. Overall, 34% less irrigation was applied under the variable-rate irrigation regime, and a reduction of 21.3% in energy cost was estimated (Table 5.1). These savings were achieved within some parts of the field that were over-irrigated by constant-rate irrigation. About 15% of the experimental site was flooded in the 2013 and 2014 growing seasons due to lack of a drainage system. Water accumulated in low elevation areas after rainfall, irrigation or runoff from higher elevation areas. Thus, ponds formed on 15% of the site and made irrigation unnecessary due to loss of crop on those areas. In addition to the flooded areas, water was not applied to areas such as roads and non-cropped spots within the experimental site using the newly-installed VRI system in the 2013 and 2014 growing seasons.

5.3.3 Crop yields (2013)

There were low crop yields in plots 1 to 5 which were located at the southernmost-portion of B1 in MZ1. The low crop productivity was attributed to the persistence of high soil water content in the low elevation areas during the 2013 growing season. Higher soil moisture level, particularly in the low elevation and high EC areas, during the 2013 growing season had negative impact on the wheat crop production due to the heavy rainfall in June. In addition, the occasional severe thunder storms and hails damaged the overall wheat crop in the experimental site in June 19, 2013.

An ANOVA was performed and significance levels were set at the 5% level using the student t-test. It can be seen from the data in Table 5.2 that the crop grain yields were significantly ($P<0.05$) different among the two management zones and among irrigation treatments. Average yields within the experimental plots in the low elevation and high EC area (MZ1) and in the medium EC and medium elevation area (MZ2) were 2.36 t/ha and 2.76 t/ha, respectively (Table 5.3). As shown in Table 5.4, greater water application (25%) resulted in significant crop yield improvement and no significant reduction in crop yield was found with 25% less irrigation application. Irrigation management is a complex task in fields with an extensive spatial and temporal variability. The characterization of soil moisture is highly relevant for irrigation application to ensure increased crop production in the low productive areas. Uniform application of irrigation over the experimental site where elevation is highly variable not only causes water wastage but also limits crop production.

5.3.4 Soil water tension (2013)

Further investigation showed that, there were differences between the daily soil water tension measured within the irrigation treatments and among the management zones. In Figures 5.4-5.6 there is a clear trend of increasing the soil water tension over the growing season for the 30 cm depth. The intense rainfall in June maintained the soil water tension around -5 kPa for the irrigation treatments in the MZI due to lack of drainage system to evacuate the excess water until mid-July (Fig. 5.4). The soil water tension started to rise after pumping the ponded water out of the experimental site. The soil water tension fluctuated during the four irrigation cycles on 16 July, 19, 21, and 27 August as a function of the irrigation events. The low and normal irrigation treatments had lower soil water tension than the high irrigation treatments because majority of the low and normal irrigation treatments were under saturated conditions. However, the soil water tension was fluctuated between the field capacity (28.4%) and the maximum allowable depletion (22.5%) corresponding to -5 to -20 kPa throughout most of the 2013 growing season.

In MZ2, the soil water tension started to rise in early July and reached above -30 kPa in August (Fig. 5.5). Irrigations were performed on 16 July, 19, 21, and 27 August and the soil water tension ranged from 0 to -30 kPa for the 30 cm depth until the end of August.

Comparing the soil water tension trend in the two management zones, it can be seen that the soil water tension was higher in the MZ2 throughout the growing season (Fig. 5.6). This result may be explained by the fact that the soil water tension in this particular field was mainly a function of field topography. It may be the case therefore that the field elevation difference was main driver of the crop yield variability across the field. Therefore, elevation could be a major factor causing uneven distribution of the soil water content in crop root zone and limits the uniform crop productivity in this study site.

5.3.5 Crop yields (2014)

In the 2014 growing season, wheat grain yields were collected from the three different experimental blocks within the three management zones. An ANOVA was carried out to compare crop yields within irrigation treatments and among the management zones. The statistical analysis indicate that the grain yields were significantly ($P<0.05$) different among the three management zones, but not between the irrigation treatments (Table 5.5 and 5.7). As Table 5.6 shows, the highest grain yield (4.75 t ha^{-1}) was in MZ3 and the lowest grain yield (2.23 t ha^{-1}) was in MZ1 and the grain yield was 4.26 t ha^{-1}in MZ2. No significant reduction and increase in crop yields were found by deficit irrigation and that could be attributed to rainfall intensity and irrigation frequency during the 2014 growing season. However, there are significant crop yield differences within the three management zones and irrigation management using a VRI technology is an effective approach to improve yield production in the low yielding areas within the experimental site.

5.3.6 Soil water tension (2014)

Several rainfall events from the early May until mid-July maintained the soil water tension around -5 kPa within the irrigation treatments and management zones. The soil water tension trend for three irrigation treatments and among the three management zones for the 30 cm depth are shown in Figures 5.7 to 5.10. From the data in Figure 5.7, it is apparent that the water ponding in the low elevation area, where the MZ1 was located, maintained the soil saturated for approximately 4 weeks longer than the two other management zones. The early season water logging in the MZI damaged the crop growth significantly and reduced the average crop yields in the MZI.

Irrigation events were commenced on 10 July after the soil water tension raised in MZ2 and MZ3 (Figs 5.8 and 5.9). Over the 2014 growing season, six irrigation events were performed. The late season rainfall reduced the soil water tension level in all experimental plots as shown in Figures 5.7 to 5.10.

5.3.7 Crop model simulation under the three management zones

Model calibration was performed using the experimental data sets which were collected during the 2013 growing season within two management zones including 18 experimental plots. There was good agreement between the measured and simulated grain yield in 2013 (R^2=90) (Fig. 5.11). The performance of the calibrated model was evaluated using the experimental data sets collected during the 2014 growing season within three management zones including 27 experimental plots.

The simulated grain yield agreed well with the measured yield in 2014 (R^2=91) (Fig. 5.12). The root mean square error (RMSE) for both calibration and validation process were 0.66 and 0.44 t ha^{-1}, respectively. After model calibration and validation, various water application rates were input to the models, to predict crop yields under the three management zones in the 2014 growing season. In 2014 season, the mean measured wheat grain yield for three management zones (MZ1, MZ2, MZ3) were 2.41, 4.28, and 4.71 t ha^{-1}, respectively. While, the mean predicted wheat grain yield for three management zones (MZ1, MZ2, MZ3) were 3.6, 5.72, and 6.47 t ha^{-1}, respectively (Table 5.8). This significant difference can be attributed to frequent heavy rainfall and storm in mid-June which caused significant crop yield loss in the study site. It is apparent from the simulated water production functions (Fig. 5.13), to achieve optimum crop yield production, irrigation application of 175 mm over the length of the growing season was needed. While, the mean irrigation application depth was 104 mm during six irrigation events between 9th July and 9th August. Based on the simulation of crop grain yield, more frequent irrigations over the irrigation season specifically in the crop development stage is needed to increase crop yield production in the study site.

5.4 Conclusions

This study has investigated the potential water and energy savings, and crop productivity benefits of variable-rate irrigation (VRI) technology. Water and energy consumption under variable and constant rate applications were assessed during two growing seasons for a 27 ha field under a center pivot irrigation system (CPIS). Overall, 25% and 34% less water was applied under the VRI during the 2013 and 2014 growing seasons, respectively. The water and energy savings in the experimental site were achieved under the generated prescription maps based on elevation and EC

parameters. However, the water and energy consumtion with VRI technology strongly depends on site-specific prescription maps. It can therefore be assumed that the potential benefits of VRI technology would be promising with developing well-tailored prescription maps.
It is estimated that energy saving of 18% could be realized by optimum water application. The estimated energy cost savings by using VRI technology under CPIS were 15% and 21% during the 2013 and 2014 growing seasons.

Higher water application in a low elevation and high EC areas resulted no significant improvement on spring wheat yield, but by applying more irrigation in a high elevation and low EC area, the crop yield increased. Overall, during the 2013 and 2014 growing season, crop yields were significantly different among the three management zones. Furthermore, crop simulation in the 2014 growing season indicated that, the crop yield could have improved with optimized irrigation applications and implementation of drainage system.

The most obvious finding in the current study is the significant water and energy saving benefits from the VRI. These findings enhance our understanding of the potential benefits of VRI technology, therefore VRI has a potential to improve water and energy consumption, and crop yield under site-specific management. This research project was limited to one irrigated field, thus it is recommended that further research be undertaken in different locations under different crops to highlight the benefits and challenges of VRI technology for water and energy savings and crop production strategies.

5.5 Acknowledgment

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for financial support and they would like to thank the Alberta Irrigation

Technology Center for providing equipment and extensive in-kind support. The authors are also thankful to Brian Cook and Mike Ellefson, Alberta Agricultural and Forestry, and Kenton Ollivierre, McGill University, for technical assistance.

Table 5.1 Pump operational costs of VRI and CRI for the 2013 and 2014 growing seasons

System information	CRI 2013	VRI 2013	CRI 2014	VRI 2014
Irrigated depths (mm)	90	67.5	90	58.6
Electricity price[1] ($CAD/kwh)	0.094	0.094	0.082	0.082
Electricity cost ($ CAD/year)	937	713	876	586
Water consumption reduced (%)	0	25	0	34
Pump operational costs reduction (%)	0	15.6	0	21.3

1. Electricity price is the average energy cost for the growing season from May to August

Constant rate irrigation (CRI), Variable rate irrigation (VRI)

Table 5.2 P-values for the management zones and irrigation treatments (95% confidence)

Source	DF	Sum of Squares	F Ratio	P-values
Management zones	1	1.48	30.92	<.0001*
Irrigation treatments	2	0.46	4.79	0.0148*

* Significand in 95% level

Table 5.3 Mean wheat grain yields measured within management zones in the 2013 growing season

Management Zones	Std Error	Mean
MZ1	0.07	2.36[a]
MZ2	0.04	2.76[b]

a, b, Levels not connected by same letter are significantly different

Table 5.4 Mean wheat yields measured within irrigation treatments in the 2013 growing season

Irrigation Treatments	Std Error	Mean
HI	0.06	2.73[a]
LI	0.08	2.61[b]
NI	0.07	2.59[b]

a, b, Levels not connected by same letter are significantly different,
HI: high irrigation, NI: normal irrigation, LI: low irrigation

Table 5.5 P-values for the management zones and irrigation treatments (95% confidence)

Source	DF	Sum of Squares	F Ratio	Prob > F
Management zones	2	122.45	122.46	<.0001*
Treatments	3	1.58	1.05	0.3735

* Significant in 95% level

Table 5.6 Mean wheat grain yields measured within management zones in the 2014 growing season

Management zones	Std Error	Mean
MZ1	0.12	2.23[a]
MZ2	0.12	4.26[b]
MZ3	0.12	4.75[c]

a, b, c, Levels not connected by same letter are significantly different

Table 5.7 Mean wheat yields measured within irrigation treatments in the 2014 growing season

Irrigation treatments	Std Error	Mean
NI	0.14	3.83[a]
LI2	0.14	3.64[a]
LI1	0.14	3.89[a]
RF	0.15	3.79[a]

a, Levels not connected by same letter are significantly different

NI: normal irrigation, LI1: low irrigation 1, LI2: low irrigation 2, RF: rainfed

Table 5.8 The mean measured and simulated wheat grain yields within the three management zones in the 2014 growing season

Management zones	Measured yield ($t\ ha^{-1}$)	Simulated yield ($t\ ha^{-1}$)	Potential yield increase ($t\ ha^{-1}$)
MZ1	2.41	3.6	1.19
MZ2	4.28	5.72	1.44
MZ3	4.71	6.47	1.76

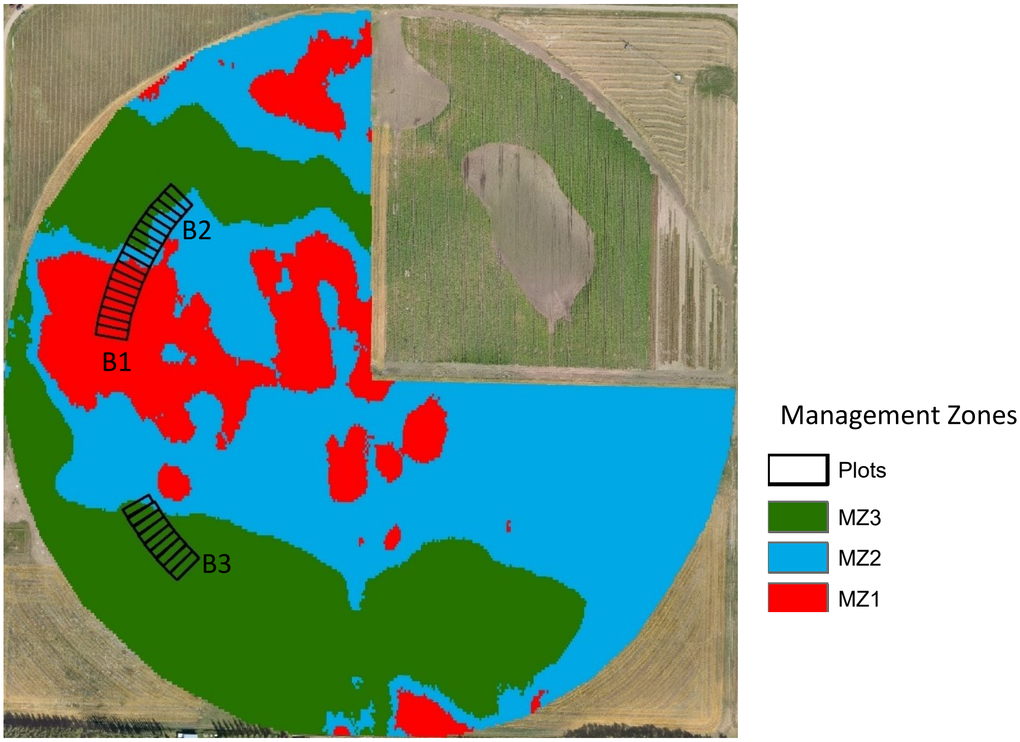


Figure 5.1 The management zones and experimental blocks (B1, B2, and B3) location

B1	LI	LI	NI	HI	NI	LI	HI	NI	HI
	*	*	*	*	*	*	*	*	*
	1	2	3	4	5	6	7	8	9

B2	NI	NI	LI	HI	HI	LI	NI	HI	LI
	*	*	*	*	*	*	*	*	*
	10	11	12	13	14	15	16	17	18

Figure 5.2 Sequence of experimental plots, irrigation treatments, and approximated location of soil tension sensors (*) in the 2013 growing season (normal irrigation (NI), low irrigation (LI), and high irrigation (HI))

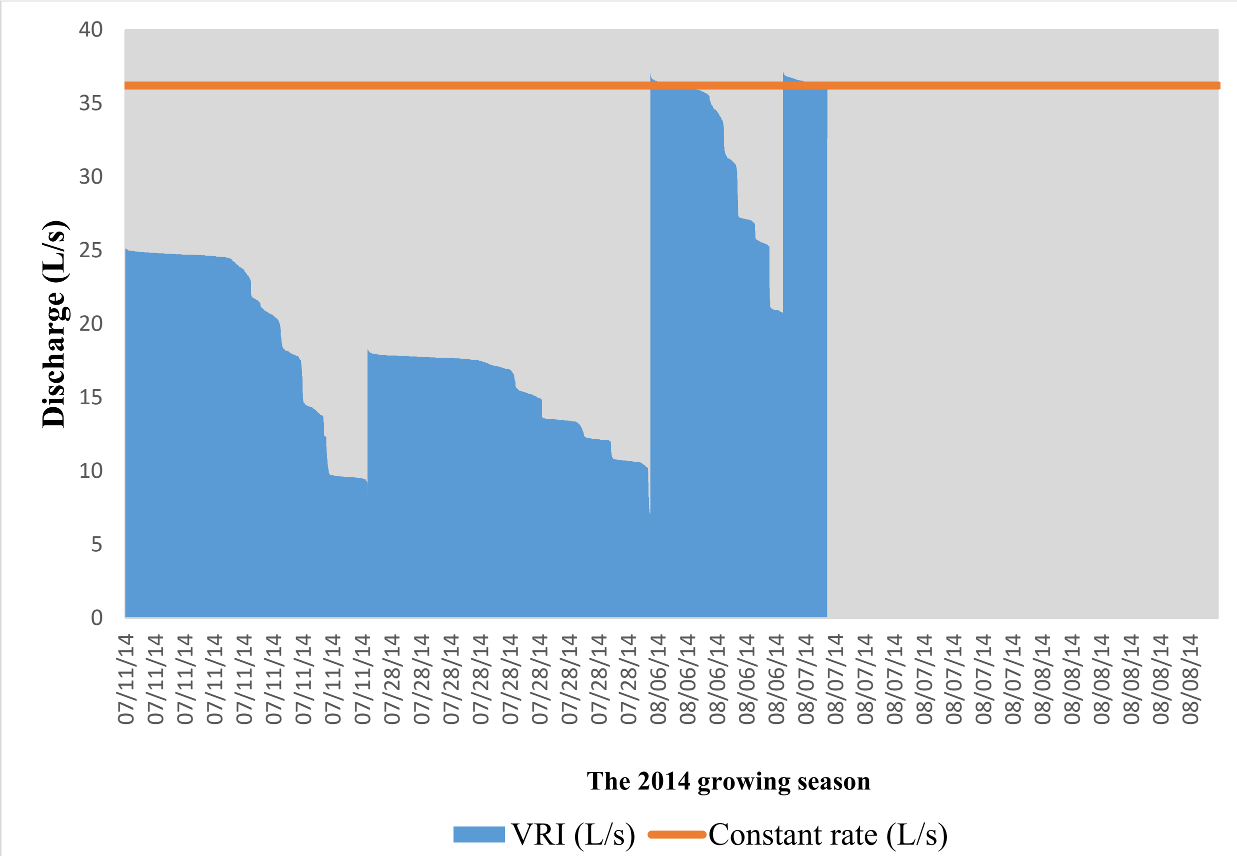


Figure 5.3 Water discharge during five irrigation cycles in July and August 2014 under variable and constant rate irrigations

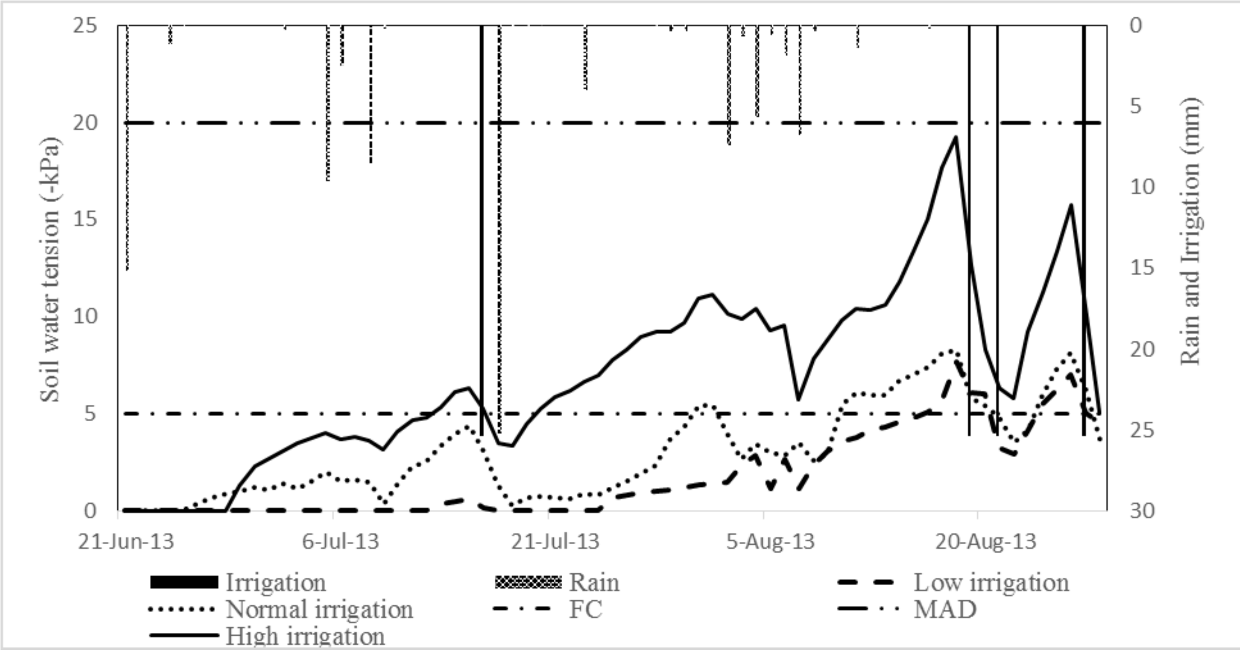


Figure 5.4 The 2013 soil water tension for irrigation treatments at depth 30 cm within MZ, (FC: field capacity, MAD: management allowed depletion)

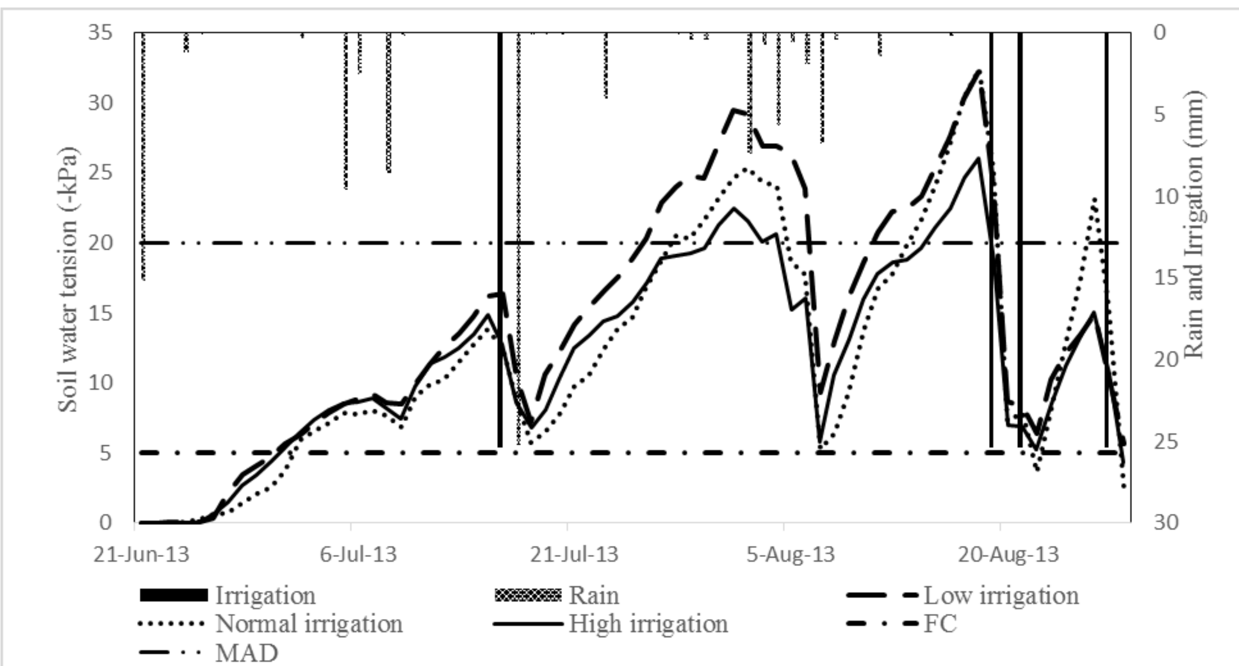


Figure 5.5 The 2013 soil water tension for irrigation treatments at depth 30 cm within MZ2, (FC: field capacity, MAD: management allowed depletion)

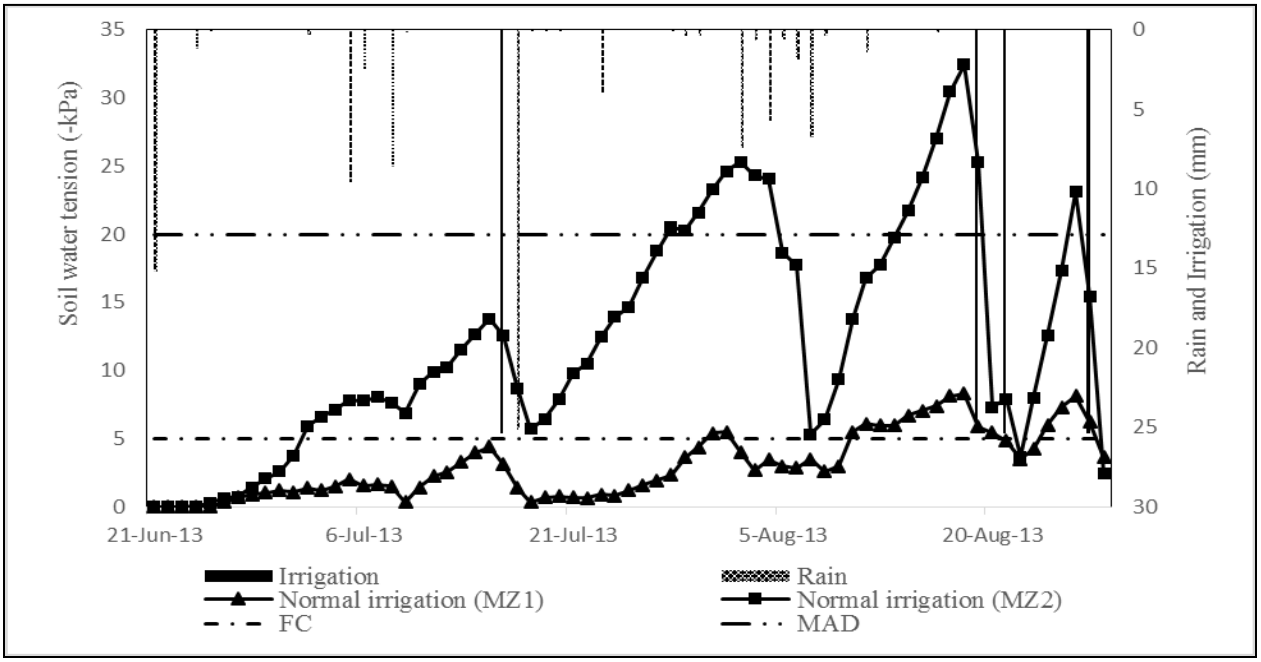


Figure 5.6 The 2013 soil water tension for the normal irrigation treatments at depth 30 cm within MZ1 and MZ2, (FC: field capacity, MAD: management allowed depletion)

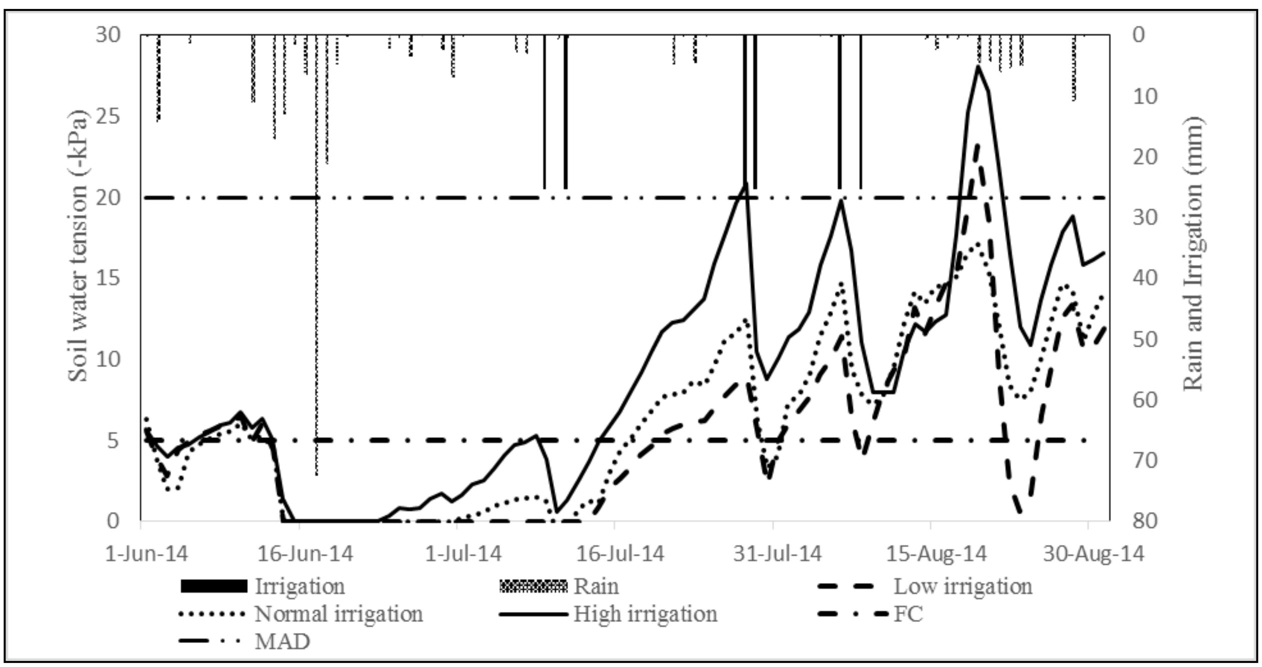


Figure 5.7 The 2014 soil water tension for irrigation treatments at depth 30 cm within MZ1, (FC: field capacity, MAD: management allowed depletion)

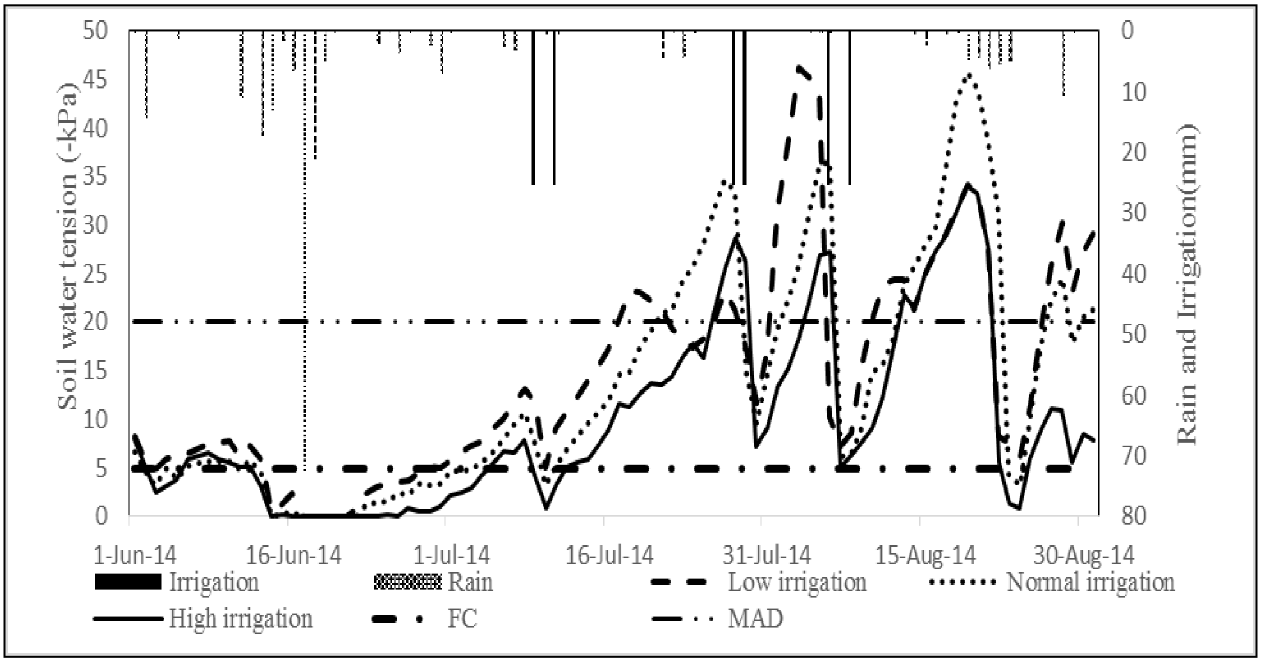


Figure 5.8 The 2014 soil water potential for three irrigation treatments at depth 30 cm within MZ2, (FC: field capacity, MAD: management allowed depletion)

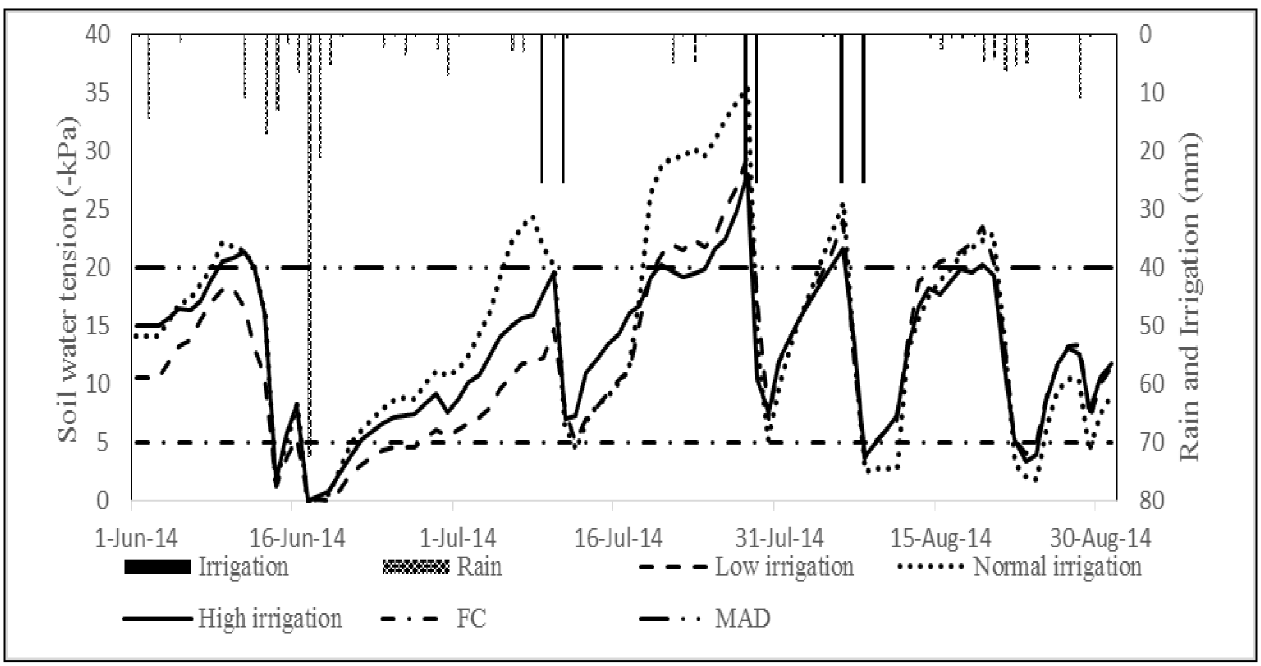


Figure 5.9 The 2014 soil water potential for the three irrigation treatments at depth 30 cm within MZ3, (FC: field capacity, MAD: management allowed depletion)

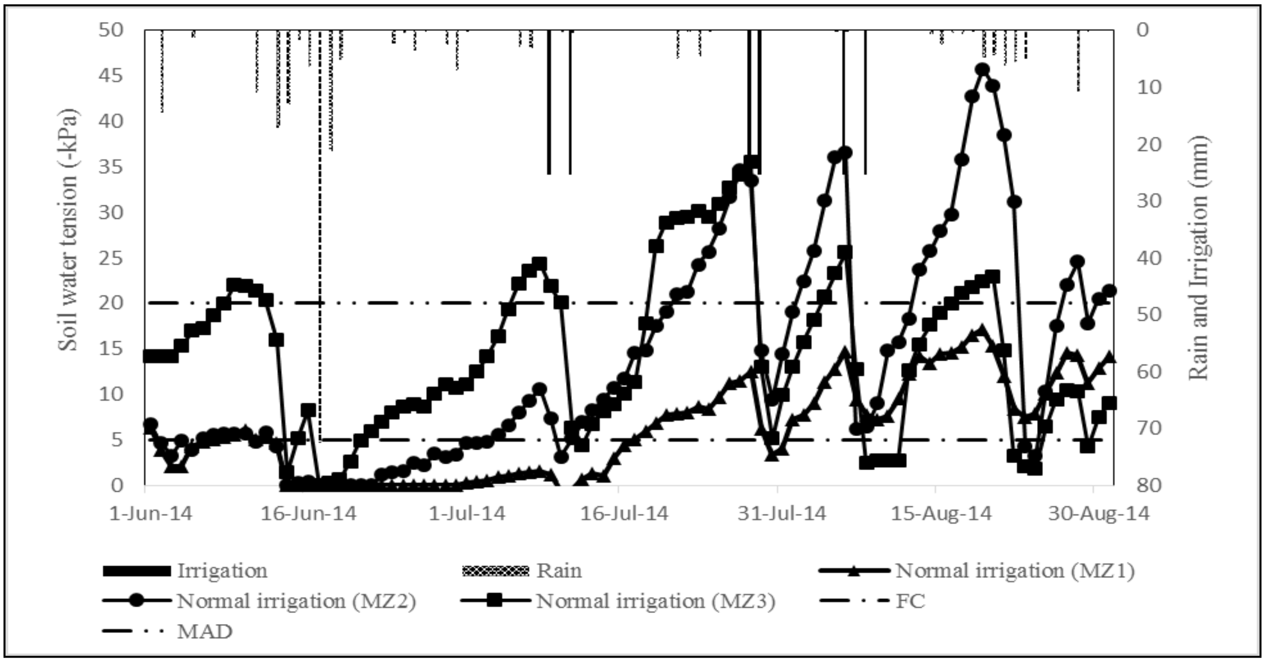


Figure 5.10 The 2014 soil water potential for the normal irrigation treatments at depth 30 cm within MZ1, MZ2, and MZ3, (FC: field capacity, MAD: management allowed depletion)

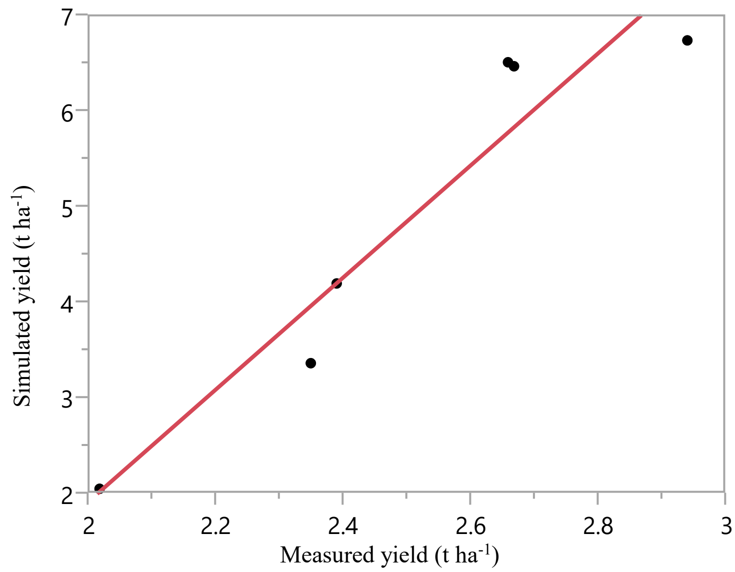


Figure 5.11 The simulated versus measured grain yield in the growing season 2013 (calibration)

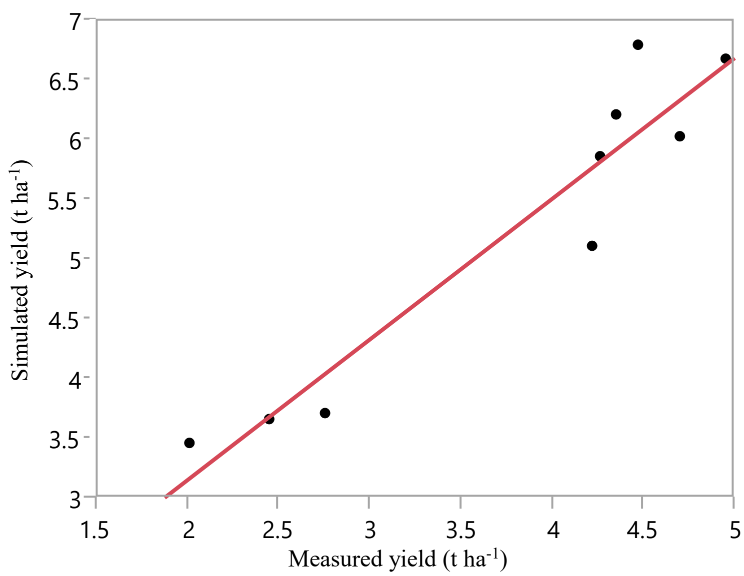


Figure 5.12 The simulated versus measured grain yield in the growing season 2014 (validation)

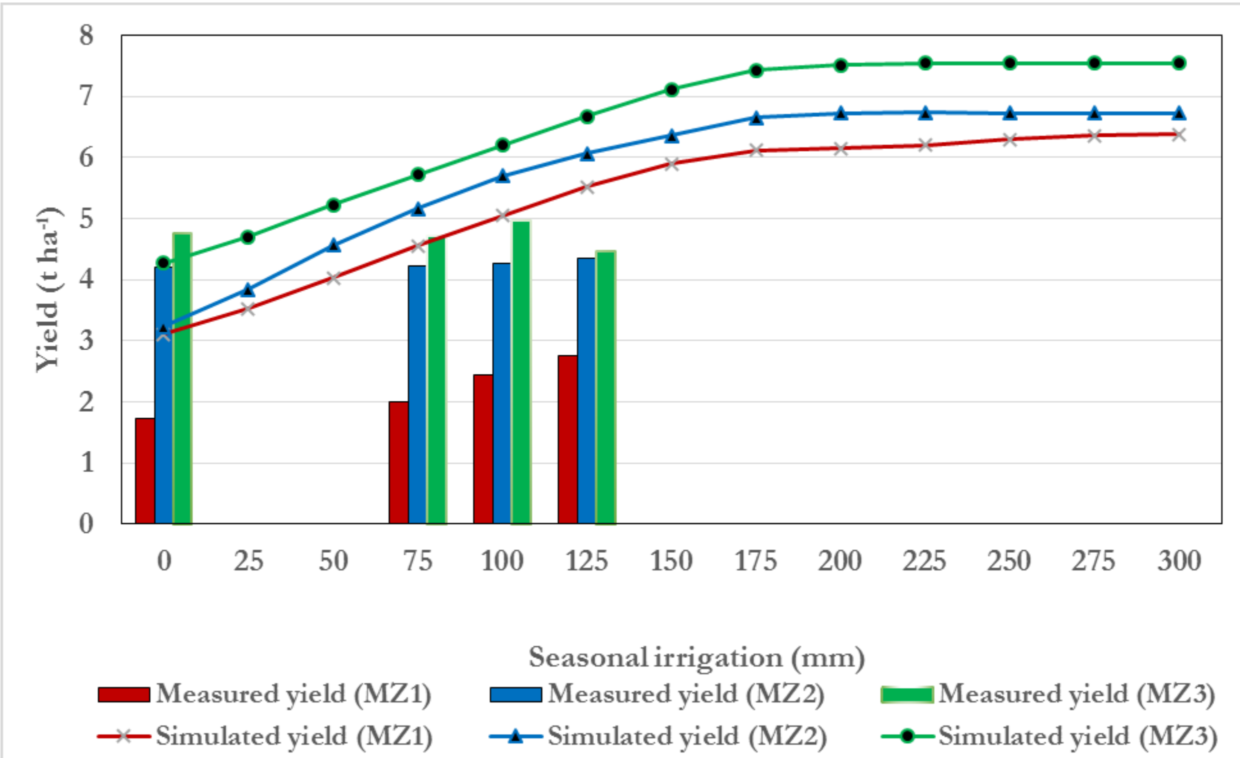


Figure 5.13 The simulated water production functions for the three management zones in the growing season 2014

Connecting text to Chapter 6

This Chapter is a manuscript submitted for publication in Irrigation Science. The manuscript is co-authored by Dr. Chandra A. Madramootoo, Shelley A. Woods, Viacheslav I. Adamchuk, and Laura Gilbert. All literature cited in this chapter is listed in the reference at the end of this thesis.

Chapter six covers application of VRI for potato productivity and therefore discusses objective four of this research. As presented in Chapter one, this paper addresses the knowledge gap in the potential crop production benefits of VRI technology. This is the topic of the following article.

"Application of Variable-Rate Irrigation for Potato Productivity"

Contributions made by the different authors are as follows;

1. Aghil Yari, Ph.D. Candidate, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
2. Chandra A. Madramootoo, the thesis supervisor, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
3. Shelley A. Woods, Irrigation and Farm Water Division, Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada.
4. Viacheslav I. Adamchuk, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.
5. Laura Gilbert, Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada.

The principal author was responsible for preparing the experimental design and methodology, conducting the field work, analyzing data, and the documentation. Prof. Chandra A. Madramootoo, is the thesis supervisor who provided suggestions and proofreading of the manuscript. Dr. Shelley A. Woods provided the extensive technical assistant for conducting the field experiments. She also provided suggestions and proofreading of the manuscript. Dr. Viacheslav I. Adamchuk provided the technical suggestions and proofreading of the manuscript. Mrs Laura Gilbert provided the assistant in collecting the field data and writing a report for the 2015 growing season.

Chapter 6

Application of Variable-Rate Irrigation for Potato Productivity

Aghil Yari[1], Chandra A Madramootoo[2], Shelley A Woods[3], Viacheslav I. Adamchuk[4], Laura Gilbert[5]

[1, 2, 4,5] Department of Bioresource Engineering, McGill University, Ste-Anne-De-Bellevue, Quebec, Canada

[3] Irrigation and Farm Water Division, Alberta Agriculture and Forestry, Lethbridge, Alberta, Canada

Abstract

Variable-rate irrigation (VRI) has the potential to increase yields and reduce water consumption and energy costs. Spatial and temporal variability of soil and field properties can impact the efficiency of irrigation and crop yield. The VRI technology allows for the precise application of irrigation to meet crop water demands in controlled amounts prescribed for specific management zones within a field. Sensitivity to over and under-irrigation and the high water requirements of potato make the crop a good candidate for site-specific irrigation management. The use of VRI to conserve water and obtain high quality potato production was tested in Southern Alberta, Canada during the 2015 and 2016 growing seasons. Exceptionally dry weather in 2015 resulted in a total of 21 irrigation events. Overall, 43% less water was applied under the VRI, and a 12% reduction in irrigation pumping cost was achieved. The crop in plots receiving normal irrigation (361 mm per season) produced a slightly lower yield than plots receiving high irrigation (480 mm per season), but produced the best quality in terms of uniformity of size and glucose content of the

tubers. In 2016, there were no significant differences between potato yield and quality within the irrigation treatments due to significant amounts of precipitation during the growing season.

Keywords: Potato productivity, water saving, energy cost, center pivot irrigation system, potato yield, and tuber quality.

6.1 Introduction

Site-specific management (SSM) is becoming increasingly in demand due to the limitations of conventional agricultural practices. Spatial and temporal variations are major factors that contribute to within-field crop-yield variation. The SSM is the most effective means to eliminate negative impacts of spatial and temporal variations and reduce within-field crop-yield variation. Also, site-specific water application can profoundly improve water and energy consumption, limit the movement of soil nutrients, decrease surface runoff, reduce non-uniformity of irrigation and fertilizer, and improve crop quantity and quality. Adoption of a SSM strategy is becoming popular on irrigated fields of southern Alberta due to spatial and temporal variability. Therefore, growers in southern Alberta have attempted to utilize a VRI technology to practically manage a field variability and improve crop yields. The VRI reduces the negative effects of field spatial and temporal variability on crop yield and it can amplify water use efficiency and therefore can increase water security of a region. Reducing or eliminating areas of excess irrigation applications within a field will reduce the potential for runoff and pond formation, creating conditions for improving crop yield and quality (Evans and Saldler, 2013). The VRI technology optimizes water application depth by controlling of individual or group of sprinkler and travel speed of the center pivot irrigation system (CPIS) (Sui and Fisher, 2015). Natural spatial field variability results in uneven absorption of water (Xiang et al., 2007) due to differences in elevation, and soil properties, such as texture and electrical conductivity (EC). Uneven field elevation can result in dry zones in high elevation and ponding in lower elevation zones. Management zones (MZ) can be created taking soil and topographic variations into account in order to define areas of a field with similar water requirements (Xiang et al., 2007). Redulla et al (2002) studied the effects of spatial variability of pH, nutrient availability, and soil texture on four commercial potato fields. They concluded that soil texture had the strongest correlation with yield because it was an indicator of available water holding capacity.

Russet Burbank potato is a chipping variety common to the province of Alberta. Expected potato yield in Alberta is 35 t ha^{-1} (Wood, 2013). Potatoes have high water sensitivity and require an annual total of 400-550 mm of water (King and Stark, 1997). For Russet Burbank potato, available soil water (ASW) of the root zone below 65% from planting to tuber bulking can result in lower yields (King and Stark, 1997). At the planting stage, recommended ASW is 70-80%. Excessively wet or dry soils will increase seed decay. Cold soils resulting from overwatering will delay sprouting (King and Stark, 1997). During vegetative growth, tuber initiation, and tuber bulking, the recommended ASW is 65-85% (King and Stark, 1997). A water deficit in stages 2-4 reduces leaf and stem development, affecting the rate of photosynthesis and reducing tuber development (King and Stark, 1997). A lower internal water pressure also results in malformations, which reduces tuber quality (King and Stark, 1997). During maturation, the water requirements are lower and ASW should be kept to 60-65% (King and Stark, 1997). Overwatering during skin development will result in enlarged lenticels, which create pathways for soft rot bacteria to enter the tuber (King and Stark, 1997). Prior to harvest, the field should be irrigated to increase ASW to 65% (King and Stark, 1997). Dry soil at harvest increases shattering and makes separation of tuber and soil more difficult (Alberta Agriculture and Forestry, 2011).

Sugar content is an important indicator of tuber quality. For chipping potatoes, glucose content of less than 0.33% is preferred (Storey and Davies, 1992). A specific gravity of at least 1.08 is preferred for French fries and of 1.085 for chipping (Storey and Davies, 1992).

In general, plants that have a low tolerance to drought will have a low tolerance to salinity (Cambouris et al., 2006). Salinity will have similar effects as drought, delaying growth and impeding osmosis in the plant. Potatoes have a moderate tolerance to saline soils characterized by an EC of 2 to 4 dS m^{-1} (Alberta Agriculture and Forestry, 2001).

The sensitivity to over and under-irrigation and high water requirements of potato make it a good candidate for evaluating the energy and water consumption reduction benefits of VRI. Potato has limited ability to store water for use in dry periods. Excess water results in reduced aeration, propagation of disease and increased nitrogen leaching (King and Stark, 1997).

The first objective of this study was to investigate the use of a VRI technology to improve the quality and quantity of Russet Burbank potatoes in Southern Alberta. The second objective was to assess the performance of the system for the potential water and energy cost savings.

6.2 Materials and methods

6.2.1 Site description and irrigation system

A two-year field experiment was conducted at the Alberta Irrigation Technology Centre (AITC) located in southern Alberta (latitude 49.69º N and longitude 112.74º W) with a mean elevation of 905 m above sea level. Irrigation was performed using a Valley 8000 series center pivot system spanning 295 m and covering 27 ha during the 2015 and 2016 growing seasons. Each individual sprinkler was fitted with 1.2 bar pressure regulators (Nelson Irrigation, Walla Walla, Washington, USA) on flexible drop hoses spaced 2.29 m apart and 1.5 m above the ground. The system was modified for variable rate application using a VRI zone control package from Valmont Industries Inc., (Valmont Industries Inc., Omaha, Nebraska, USA).

The pivot lateral with 129 sprinklers was divided into 12 sprinkler banks. Each sprinkler bank was configured to have 10-12 sprinklers.

6.2.2 Data collection

6.2.2.1 Field properties and experimental plots location

A Real Time Kinematic (RTK) global navigation satellite system (GNSS) receiver was used to conduct a topographical survey of the field. The apparent soil electrical conductivity (EC_a) was measured using a Veris® 3100 (Veris Technologies, Inc., Salina, Kansas, USA) and EM38 instrument (Geonics Limited, Mississauga, Ontario, Canada). The Veris® 3100 was configured to provide both shallow (0-30 cm) and deep (0-90 cm) readings of EC_a. The top-right 90º sector of the study area was not mapped due to on-going farming operations. The data collected with a Veris® 3100 was included in this manuscript.

In order to remove effects of spatial variability of field properties on potato yield, the experimental plots were located in a section with similar properties. Figure 6.1 maps the elevation gradients in the field. The experimental plots had an elevation of 903-906.8. Figure 6.2 maps the EC_a gradients in the field and ranged between 17.4-174.5 mS m^{-1}. The experimental plots had an EC_a of 17.4-36.5 mS m^{-1}.

The management zone map was developed by combining the elevation and EC_a data. Figure 6.3 illustrates the three management zones of the field with all the experimental plots located in the same management zone.

Soil samples were taken at depths of 30 cm and 60 cm. The 36 samples were analyzed for nitrogen, phosphorus, potassium, organic matter content, pH, EC, and soil texture. The soil at the study site was mostly sandy clay loam (SCL).

6.2.2.2 Crop information and fertilizer application

In southern Alberta, planting takes place between the third week of April and the middle of May depending on weather conditions. Harvest occurs between the middle of September and the middle of October and depends on tuber size. The root zone is 45 cm deep with the majority of the roots found at 30 cm (King and Stark, 1997).

Russet Burbank potatoes were planted in the south eastern and south western quadrants of the experimental site on April 28, 2015 and May 2, 2016 and harvested on September 3, 2015 and September 15, 2016 growing seasons, respectively. Crop yield and quality of each plot were recorded at harvest, and averaged for the 3 plots under the same irrigation prescription. The staff at the Alberta Agriculture and Forestry, Food and Bio-Industrial Crops Branch in Brooks, Alberta, conducted the tuber quality assessments. Four samples per plot were collected. All plant measurements were taken within a 3 m row in each plot.

Fertilizer application rates were based on soil nutrient analyses and applied according to the Alberta Agriculture and Forestry recommendation. For potatoes, the Alberta Fertilizer Guide recommends nitrogen (N) application of 100-190 kg ha^{-1} in bands placed 3-5 cm away from the seeds. The experimental site was fertilized and a total of 152 kg ha^{-1} and 79 kg ha^{-1} of nitrogen (44-0-0) were applied in the 2015 and 2016 growing seasons, respectively.

6.2.2.3 Irrigation applications

Irrigation frequency and depth were recommended by Alberta Agriculture and Forestry using the Alberta Irrigation Management Model (AIMM-version 3.1.3, Alberta Agriculture and Forestry, Calgary, 2010). The model was designed to provide irrigation recommendations and to keep a record of operations. The program outputs soil moisture conditions, evapotranspiration, irrigation application amounts, surface runoff, and deep percolation. Recommendations from a local agronomist and weekly reports on crop health were also used to guide irrigation frequency and amounts.

In 2015, three irrigation treatments were applied in the south western quadrant of the study site: normal irrigation (NI) representing 100% of recommended irrigation depth, low irrigation (LI) was 50% of recommended irrigation depth, and high irrigation (HI) was 150% of the recommended irrigation depth. In 2016, three irrigation treatments were applied in south eastern quadrant of study site: normal irrigation (NI) representing 100% of recommended depth, low irrigation (LI) was 70% of recommended depth, and high irrigation (HI) was 130% of recommended depth.

Catch-cans were used to meassure irrigation depths and three catch-cans were placed per plot. The first catch-can was located in the center of the plot. The other two catch-cans were placed at approximately 3 m on either side of the first and perpendicular to the travel direction of the pivot system. To calculate evapotranspiration in the time between irrigation and water collection from the catch-can, three control catch-cans were placed by the adjacent weather station and filled with roughly 170 mL of water just before the pivot reached the experimental plots. After irrigation was complete and the water had been collected on the experimental plots, the remaining volume in the control catch-cans was recorded and an average hourly water loss rate was computed. Knowing at what time the pivot started on each plot and the time at which the water was collected on each plot, the catch-can readings were adjusted for evapotranspiration with the average hourly water loss rate from the control catch-cans.

6.2.2.4 Soil water tension

Soil tension was monitored using the Hortau (MultiSense Tx3-Web Based) soil tension sensor (Hortau Co., Quebec, Canada). Each plot was equipped with an IrrolisTM-MultiSense TX3 sensor located in the middle of the plot at a depth of 30 cm. Each sensor was paired with an IrrolisTM Com Field Station which relayed the information to a central IrrolisTM Com WEB BASE to make the information available online.

6.2.3.5 Water and energy consumption

A flow meter (AG701, Saddle Magmeter, Seametrics Incorporated, Washington, USA) was used in 2015 to record water consumption during the irrigation events. Water discharge was recorded continuously every minute using a data logger and Prolog data logger software (Version 2.3037, Lakewood Systems Ltd., Edmonton, Alberta, Canada).

Energy consumption was calculated using the Alberta Irrigation Energy Calculator (Alberta Agriculture and Forestry, 2008) based on the average energy price in the 2015 growing season. Information provided by the pumping station, such as flow rate, pump efficiency, operating hours, horsepower required, were used in calculating energy requirements (Alberta Agriculture and Forestry, 2008). The calculator also translated energy requirements to operation costs based on market value prices of energy sources.

6.2.3.6 Experimental design and statistical analysis

In the 2015 growing season, three water application treatments were applied randomly (randomised complete block design (RCBD)) in three replicates on experimental plots, resulting in nine plots. Figure 6.4 illustrates the randomized order of the plots in the 2015 growing season, where North is 0° and values increase clockwise, each plot measured 4° and was located between 196° and 232° in the ninth control zone of the fourth span. In the 2016 growing season, the experimental plots were located between 176° and 140°. Due to the circular shape of the field, the experimental plots were trapezoidal in shape. Each plot measured 22.86 m by 13.88 m by 15.47 m and had an area of 335.38 m^2. A buffer zone around the experimental plots with irrigation prescriptions identical to the adjacent experimental plots reduced error from nozzle spray overlap between the zones (ASABE, 2007).

An analysis of variance (ANOVA) was performed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA) to determine whether there were any significant differences between the means of crop yields and tuber quality among the three irrigation treatments.

6.3 Results and discussion

6.3.1 Weather condition during the 2015 and 2016 growing seasons

The 2015 growing season was dry and significant irrigation was applied from planting to harvest (April 28 to September 3). However, the 2016 growing season was wet and significant amounts of precipitation fell from planting to harvest (May 2 to September 15). The growing season precipitation amounts were 106 mm and 260 mm in 2015 and 2016, respectively. Total growing season precipitation during 2015 was significantly lower than the long-term average (237 mm) (Fig. 6.5). In 2016, the amount of precipitation received was closer to the long term average. The accumulated growing degree days (GDD) between planting and harvest were slightly (3%) greater for 2016 (1410 GDD) than for 2015 (1368 GDD). The average air temperature between planting and harvest was greater for 2016 (15.5 ºC) than 2015 (8.3 ºC) (Fig. 6.6).

6.3.2 Irrigation application depth under VRI

Tables 6.1 summarize the precipitation, evapotranspiration, and irrigation application under HI, NI, and LI. It is important to note that there was no irrigation schedule that closely matched precipitation and evapotranspiration. In particular the month of June for the normal irrigation was over-irrigated, whereas August had a deficit. Part of the reason for the water surplus can be explained by the procedure to obtain water in Alberta. Irrigation water must be ordered and used the same day so as to not cause flooding further down the irrigation canals. If the weather called for strong precipitation but the possibility was low, irrigation water was ordered and the field irrigated as scheduled for fear that it would not rain and the crop could be damaged. Should the rain event occur, the field would be over-irrigated. Moreover, looking at the prescribed versus actual irrigation depth, it is clear that the VRI system loses accuracy under lower flows.

In 2015, the expected total irrigation water for HI, NI, and LI based on what was scheduled with the VRI program was 455 mm, 295 mm, and 159 mm, respectively. The system delivered 5.5%, 22.5%, and 30.9% more water than planned for HI, NI, and LI treatments (Table 6.1).

The plots were mostly over-irrigated during the 2015 summer. On two occasions, the majority of the catch-cans recorded under-irrigation. The first was on June 8, which was characterized as having average wind speeds of 6.90 m s^{-1}. The second event was on August 6 and was also characterized by high average wind speed of 5.11 m s^{-1}.

6.3.3 Water and energy consumption

The average flow when the pivot was operating at 100% capacity was 35.70 l s^{-1} while the average flow rate when the pivot was running with VRI was 20.19 l s^{-1}. Table 6.2 represents the total cost of running a pump (Cornell 4RB-CC) to feed the center pivot irrigation system for 825 hours in a growing season, roughly the time it would have taken for the pivot to complete 21 irrigations of a 27 ha field over the course of the 2015 summer. The calculations were completed using the Alberta Irrigation Energy Calculator, which automatically inputs current market prices of energy (Alberta Agriculture and Forestry, 2008). Overall, 43% less water was applied under the variable rate irrigation, and a reduction of 12% in electricity cost was achieved.

6.3.4 Soil tension within the three irrigation treatments

Figure 6.7 is representative of soil tension in plots under different irrigation treatments during the 2015 growing season. Recommended soil tension for potatoes irrigated with sprinkler irrigation is between -20 kPa to -30 kPa at a depth of 30 cm (Wang and Shock, 2011). The spike in soil tension in the LI treatment around the middle of August is typical of a tensiometer that needs water added to the ceramic cup. The drier the conditions, the more often distilled water had to be added to the tensiometers. The mean soil tension for HI, NI, and LI treatments were -10, -17, and -36.5 kPa, respectively over the 2015 growing season.

6.3.5 Potato yields (2015)

Table 6.3 summarizes the results of yield and quality of the tubers. It is interesting to notice that the HI plots had a higher total yield and marketable yield. However, they had the largest loss of deformed or small tubers. The average tuber size in HI and LI plots was similar. They also had a larger proportion of deformed tubers compared to NI. Looking at specific gravity in particular, the solids content of tubers under HI and LI is higher than those under NI. It is not uncommon for potatoes in the processing industry to have a specific gravity in the range of 1.06 to 1.11 (Lulai and Orr, 1979). An increase in specific gravity means a decrease in fat content and an overall higher yield per potato (Lulai and Orr, 1979). However, a higher specific gravity correlates to higher shear needed to cut the tubers during processing (Ross and Porter, 1969). In many regions, potato growers try to get the highest possible specific gravities. In southern Alberta, it is the opposite situation. Potatoes usually have very high specific gravities, and as a result, the slicing blades at the processors have to be replaced more often than in other locations. So, in southern Alberta, potato growers take different measures to lower their specific gravities.

The LI treatment had a greater specific gravity than the NI treatment. The glucose content for all three treatments (HI, NI, and LI, 0.39, 0.41, and 0.35, respectively) is relatively high compared to typical values obtained for Russet Burbank variety in southern Alberta (Mazza et al., 1983). However, glucose content up to 0.5% is acceptable in the processing industry (Storey and Davies, 1992). Overall the harvest in the NI plots was uniform in quantity and quality. Although the HI plots had higher yields than the NI plots, there are other factors to consider when choosing an irrigation schedule. The first is the availability of water. Being faced with a water budget for each growing season, farmers may not have the option to try to increase watering to get better yields. There are also disadvantages for the farm management in keeping the field wetter. The first is the difficultly to navigate the field with heavy equipment. The second is the increased risk of diseases, especially fungus. Fungicide was applied weekly in the field starting in the middle of June. When conditions are dry, fungus growth is less of a threat, and the time between applications can be increased by a few days. This translates to a reduction in chemicals, fuel, and input costs. It can

therefore be concluded that the higher threat of disease, the uneven and lower quality of tubers, and the high water demand due to over irrigation, make NI much more preferable.
An ANOVA was performed and the significance level was set at the 5% level. A student t-test was used to determine which irrigation treatments were significantly different from one-another. Overall, in 2015, there were significant differences between irrigation treatments for three parameters: total yield, marketable yield, and specific gravity (Fig. 6.8 a,b,c).

Plant count (number of plants within a 3 m row) decreased with increasing irrigation due to over-irrigation but the differences were not statistically significant. Plant count and number of stems per plant were greatest for the HI treatment, but results were not significant. Total yield and marketable yield increased with increasing irrigation amount. Marketable yield includes all tubers greater than 113 g. The yield for the HI treatment was significantly greater ($P<0.05$) than for the LI treatment. The yield of deformed tubers did not show significant differences among the treatments (Fig. 6.8 d). Mean tuber weight was greatest for the NI treatment, but differences were not significant. Mean tuber weight seemed to have an inverse relationship to mean stem count results.

6.3.6 Potato yields (2016)

Overall, in 2016, there were no significant differences among irrigation treatments for yield and tuber quality (Fig. 6.9). This is likely because the differences in the amount of irrigation applied to the three treatments were very small. The total water received by the NI treatment was 540 mm (including 280 mm of irrigation and 260 mm of precipitation). The differences among the three irrigation applications were not the +/- 30% that was targeted but, rather, +6% for the HI treatment (296 mm) and -11% for the LI treatment (249 mm). These differences are even smaller, relative to total water applied (irrigation plus precipitation). Some of this can be attributed to the problems with the VRI GPS system that were applied prior to July 12 repairs; however, for the six irrigations that were applied after the repairs, the HI treatment only received close to the +30% amount on two of those applications, July 22 and August 15. The remaining four, received only +1%, +6%, +8%, and +7% on July 25, August 18, August 22, and September 6, respectively. The poor VRI performance was evident prior to GPS repair.

In 2016, the internal defect of stem end discoloration (SED) was found on tubers throughout our field and, according to the processors, many other fields this year. This discoloration refers to the appearance of a brown arc during frying at one end of a French fry. The cause is physiological and not pathogenic, and is related to environmental stress occurring during the season at the time the tubers are actively growing. Although, not statistically significant, the LI treatment had the greatest incident of SED.

6.3.7 Potato yields in 2015 versus 2016

In 2016, almost 2.5 times as much precipitation (260 mm) fell on the potato VRI site than in 2015 (106 mm). Even though less irrigation was applied in 2016, the total water received was still 16% greater in 2016 (540 mm on the NI treatment) than in 2015 (467 mm on the NI treatment) (Fig. 6.10).

The data analysis indicated that the differences between the two years were significant for all factors tested. This shows the powerful influence of weather and soil conditions. In 2016 the plant count, stem count, and deformed yield were greater than 2015. Conversely, in 2015, the total yield, marketable yield, mean tuber weight, and specific gravity were greater than 2016.

6.4 Conclusions

This study has investigated the potential water and energy savings, and crop productivity benefits of variable-rate irrigation (VRI) technology under potato crop. Water and energy consumption under variable-rate and non-variable-rate applications were assessed during the 2015 growing season for a 27 ha field under a center pivot irrigation system. Overall, 43% less water was applied, and a reduction of 12% in electricity cost was achieved.

In 2015, higher water application in the experimental plots resulted no significant improvement on potatoes yield. The harvest of tubers in normal irrigation plots proved to be more uniform in quality and size of tubers. The normal irrigation produced tubers of a larger size with lower specific gravity and higher glucose content. Furthermore, plots under normal irrigation had the lowest loss rate. Under-watered plots underperformed in every category, stressing the importance of water management under drought conditions.

In 2016, there were no significant differences among irrigation treatments for any of the yield and quality factors analyzed. This is likely because the differences in the amount of irrigation applied to the three treatments were very small due to precipitation over the growing season. The analyses indicated that the differences between the two growing seasons (2015 and 2016) were significant for all factors tested. This shows the powerful influences of weather and soil conditions.

6.5 Acknowledgment

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for financial support and they would like to thank the Alberta Irrigation Technology Center for providing equipment and extensive in-kind support. The authors are also thankful to Alberta Agricultural and Forestry, and Abhishek Kumar, McGill University, for data collection in 2016.

Table 6.1 The irrigation application, precipitation, and evapotranspiration for the 2015 growing season

Month	Precipitation (mm)	Evapotranspiration (mm)	HI (mm)	NI (mm)	LI (mm)
May	39.56	22.95	22.50	13.60	7.23
June	20.08	74.36	176.50	134.51	76.96
July	37.50	121.35	154.57	118.98	67.80
August	14.60	135.55	126.63	94.31	56.15
September	1.60	11.73	0.00	0.00	0.00
Total	113.34	367.43	480.20	361.41	208.14

HI: high irrigation, NI: normal irrigation, LI: low irrigation

Table 6.2 Pump operational costs under variable and non-variable irrigation

Energy	VRI On (The mean flow rate of 20.19 l s^{-1})	VRI Off (The mean flow rate of 34.70 l s^{-1})
Electricity	2,565 $/season	2,900 $/season

Table 6.3 The (mean ± standard deviation) of potato yields and quality factors for the three irrigation treatments in the 2015 growing season

Characteristics	HI	NI	LI
Total yield (t ha^{-1})	56.73±6.45	53.24±5.97	48.22±3.76
Marketable yield (t ha^{-1})	47.96±7.05	46.21±5.23	40.88±5.01
Mean tuber weight (g)	216.71±15.48	234.07±26.61	217.26±22.28
Specific gravity	1.091± 0.004	1.089±0.005	1.092±0.004

HI: high irrigation, NI: normal irrigation, LI: low irrigation

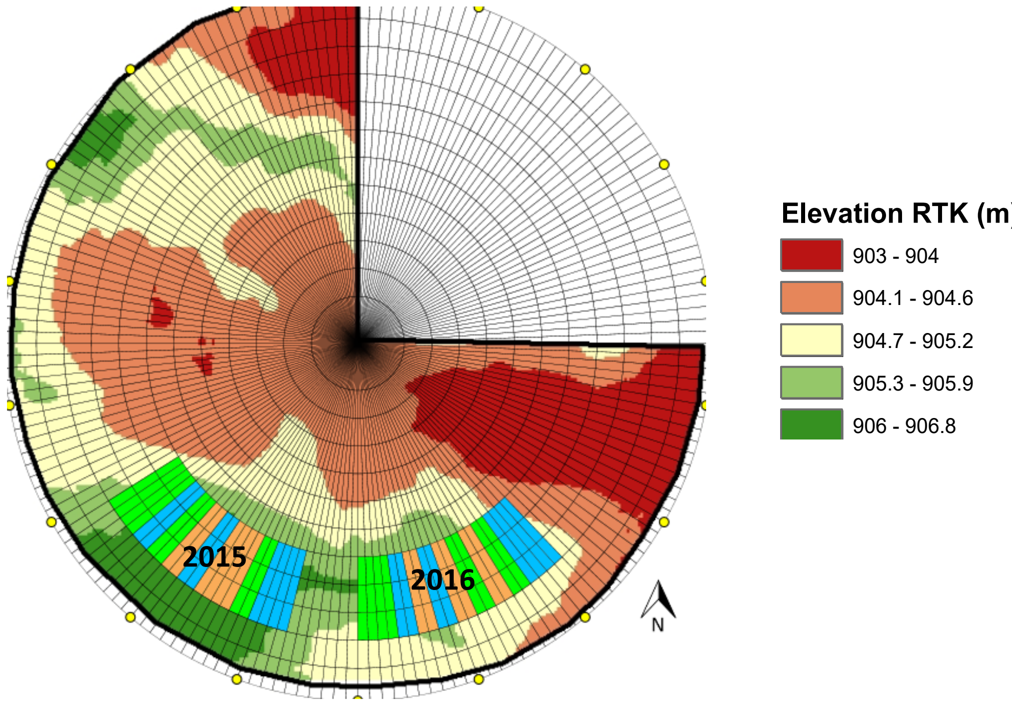


Figure 6.1 Overlay of irrigation prescription including buffer plots on elevation map in the 2015 and 2016 growing seasons

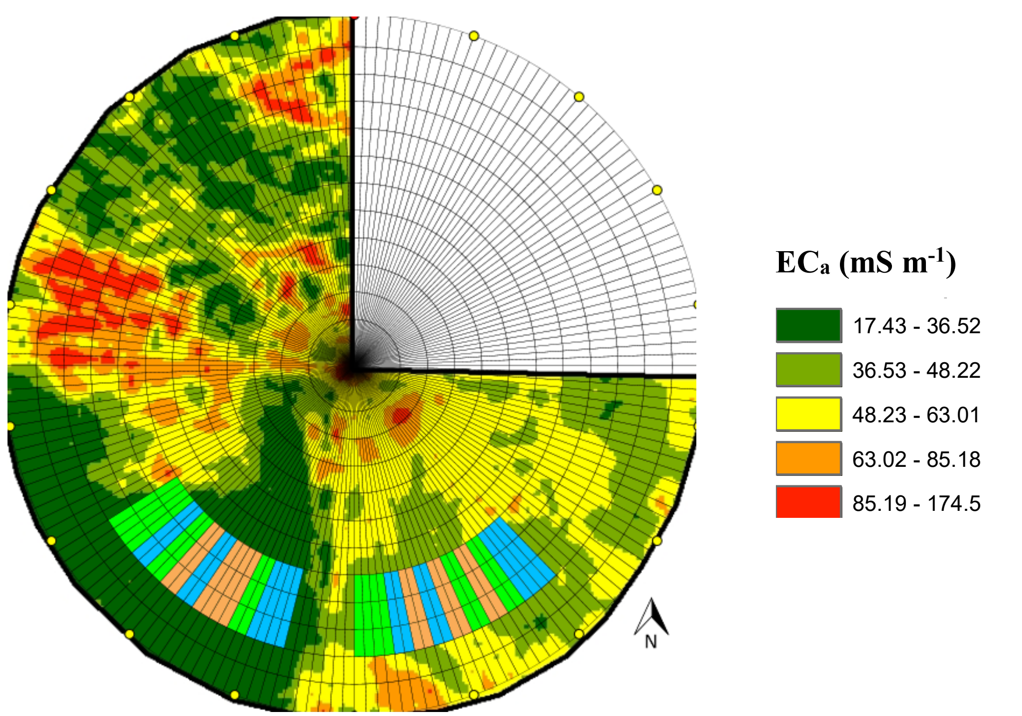


Figure 6.2 Overlay of irrigation prescription including buffer plots on EC map in the 2015 and 2016 growing seasons

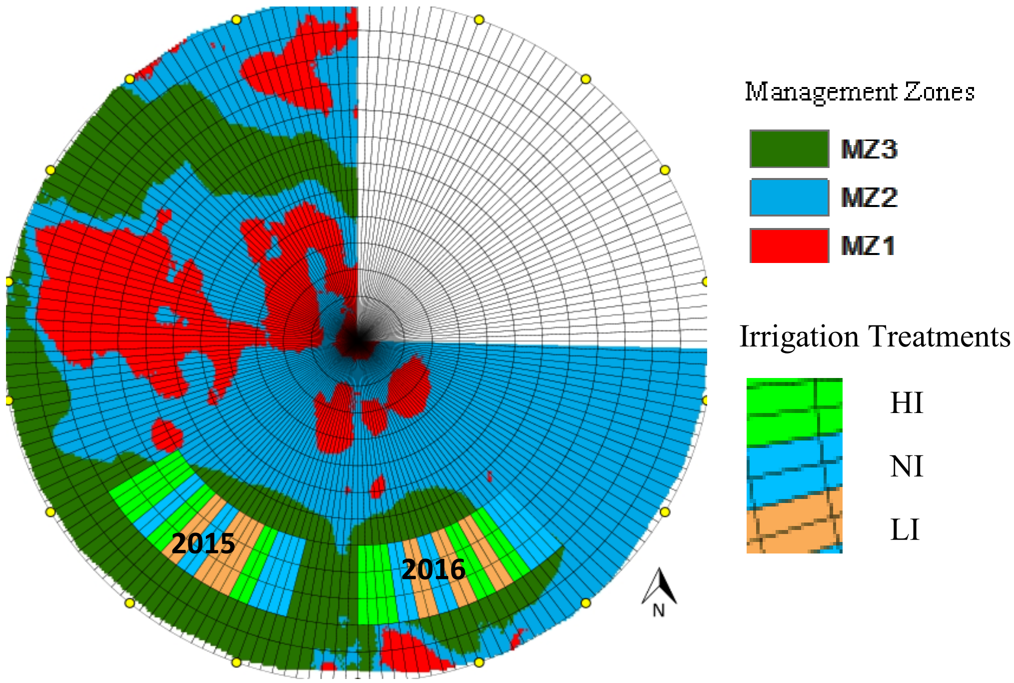


Figure 6.3 Overlay of irrigation prescription including buffer plots on management zone map in the 2015 and 2016 growing seasons

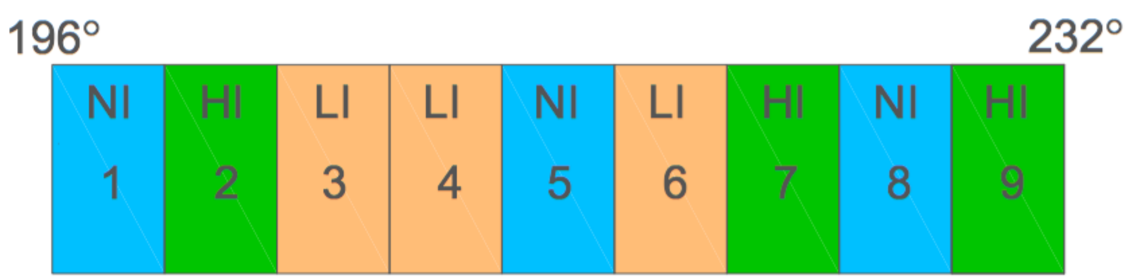


Figure 6. 4 Order of the randomized experimental plots in the 2015 growing season

HI: high irrigation, NI: normal irrigation, LI: low irrigation

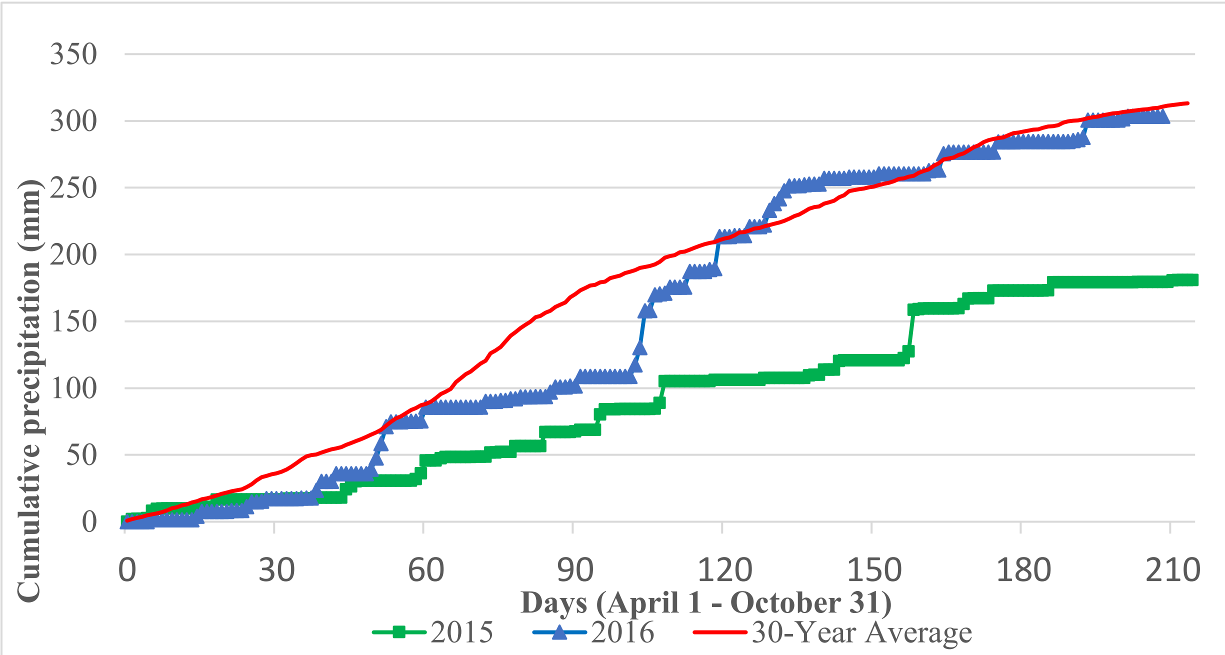


Figure 6.5 Cumulative precipitation for the 2015-2016 growing seasons and 30-year average

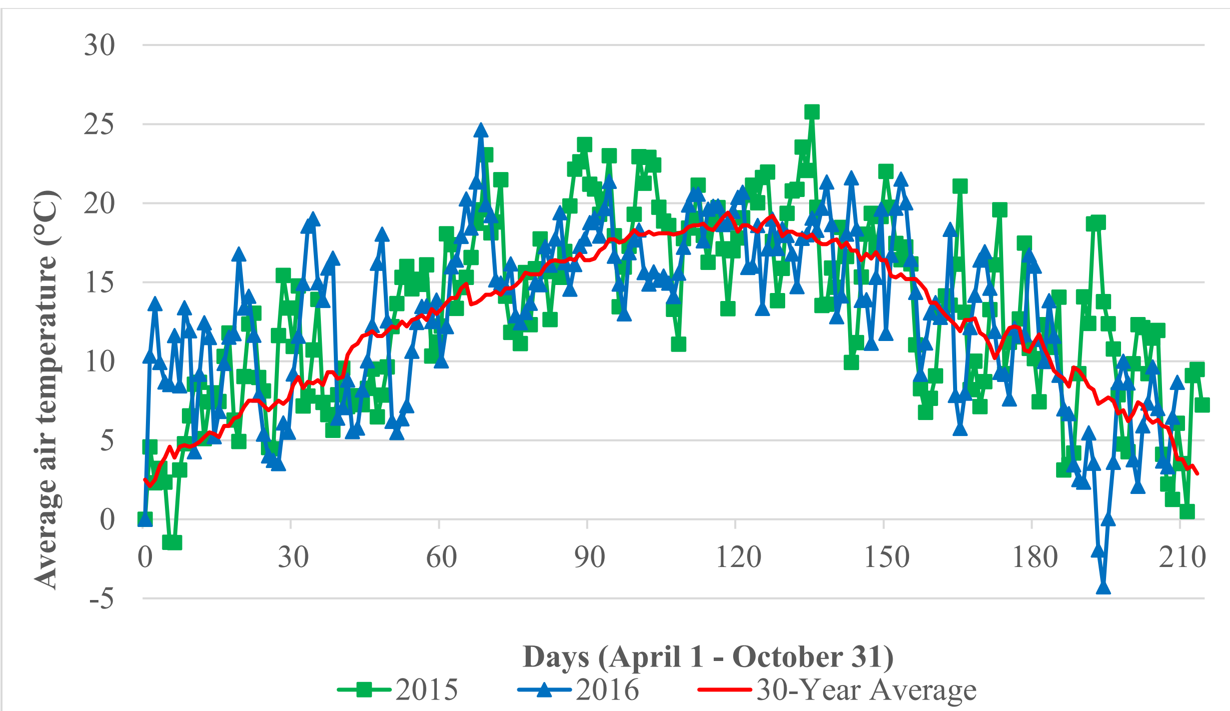


Figure 6.6 Average air temperature for the 2015-2016 growing seasons and 30-year average

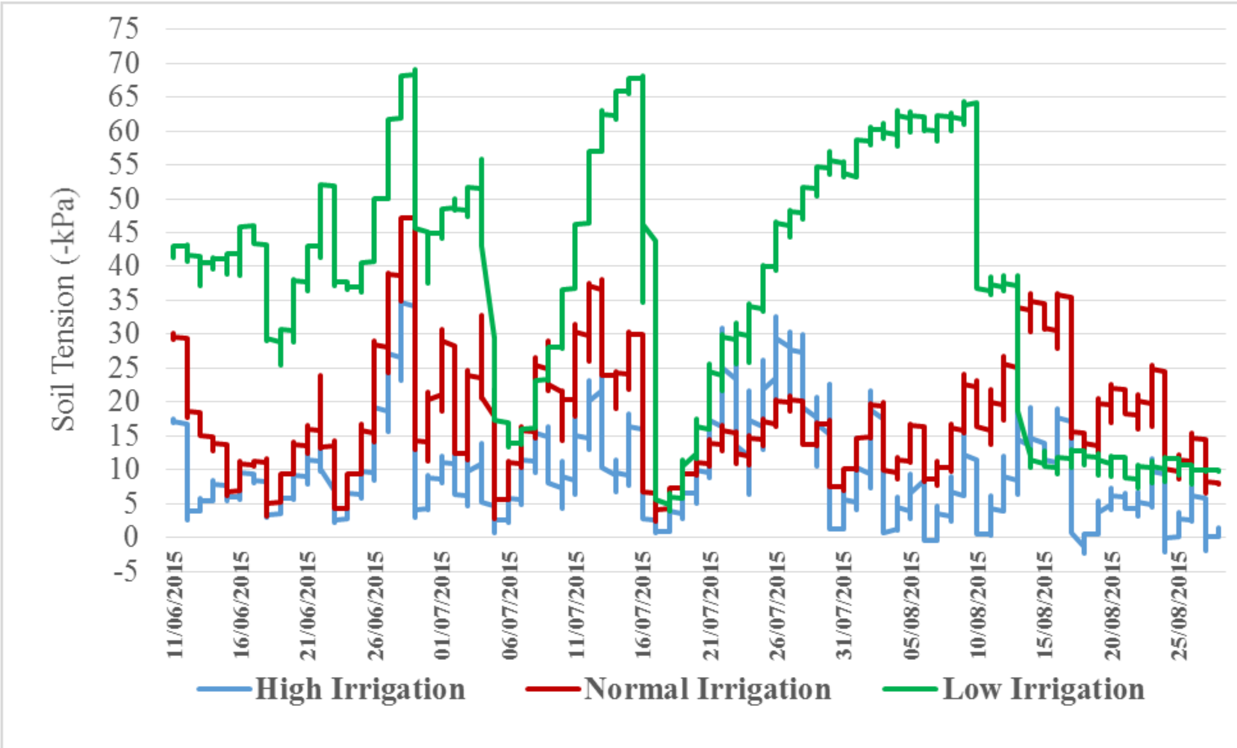


Figure 6.7 Mean daily soil tension for the three irrigation treatments during the 2015 growing season

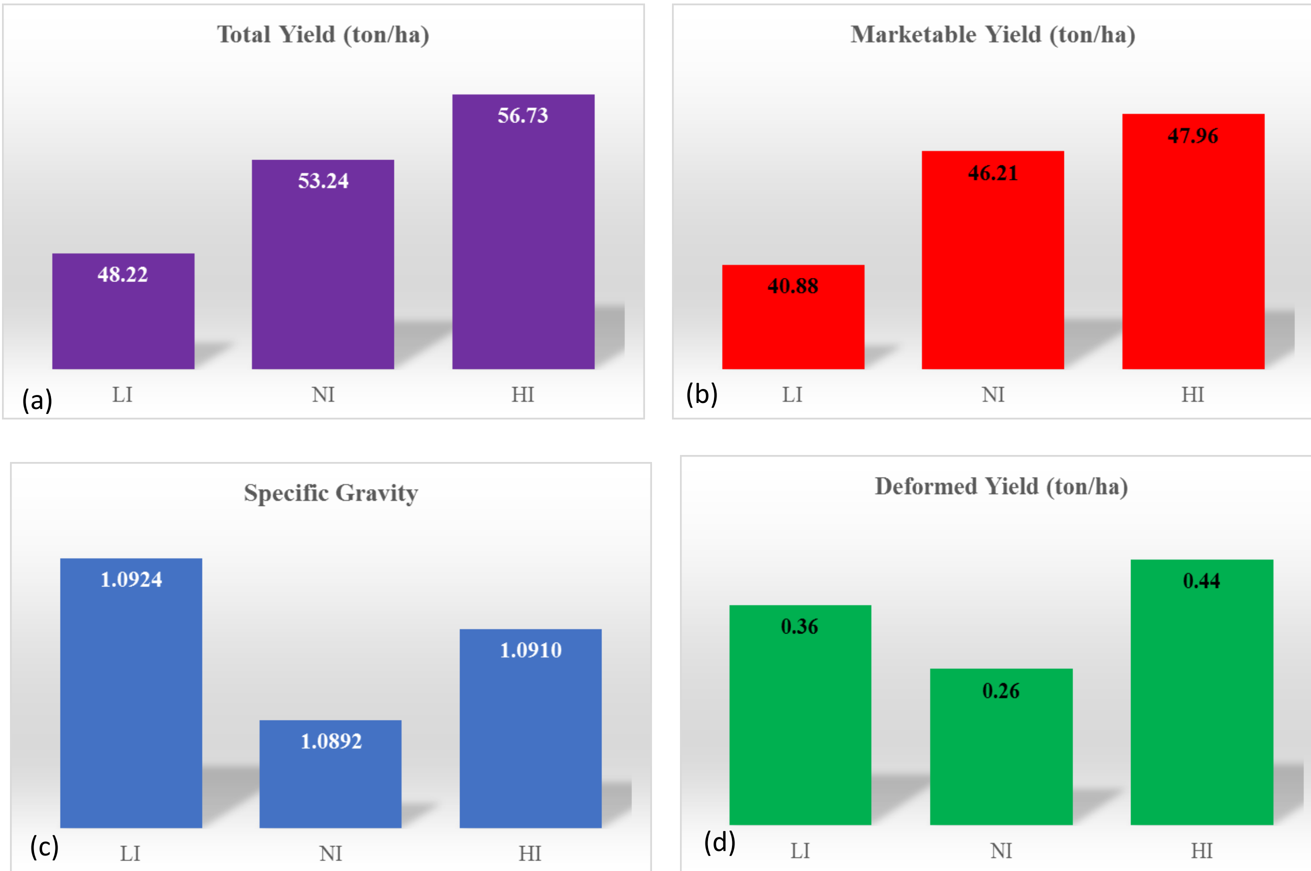


Figure 6.8 Mean total yield (a), marketable yield (b), specific gravity (c), and deform yield (d) for the three irrigation treatments in 2015, (HI: high irrigation, NI: normal irrigation, LI: low irrigation)

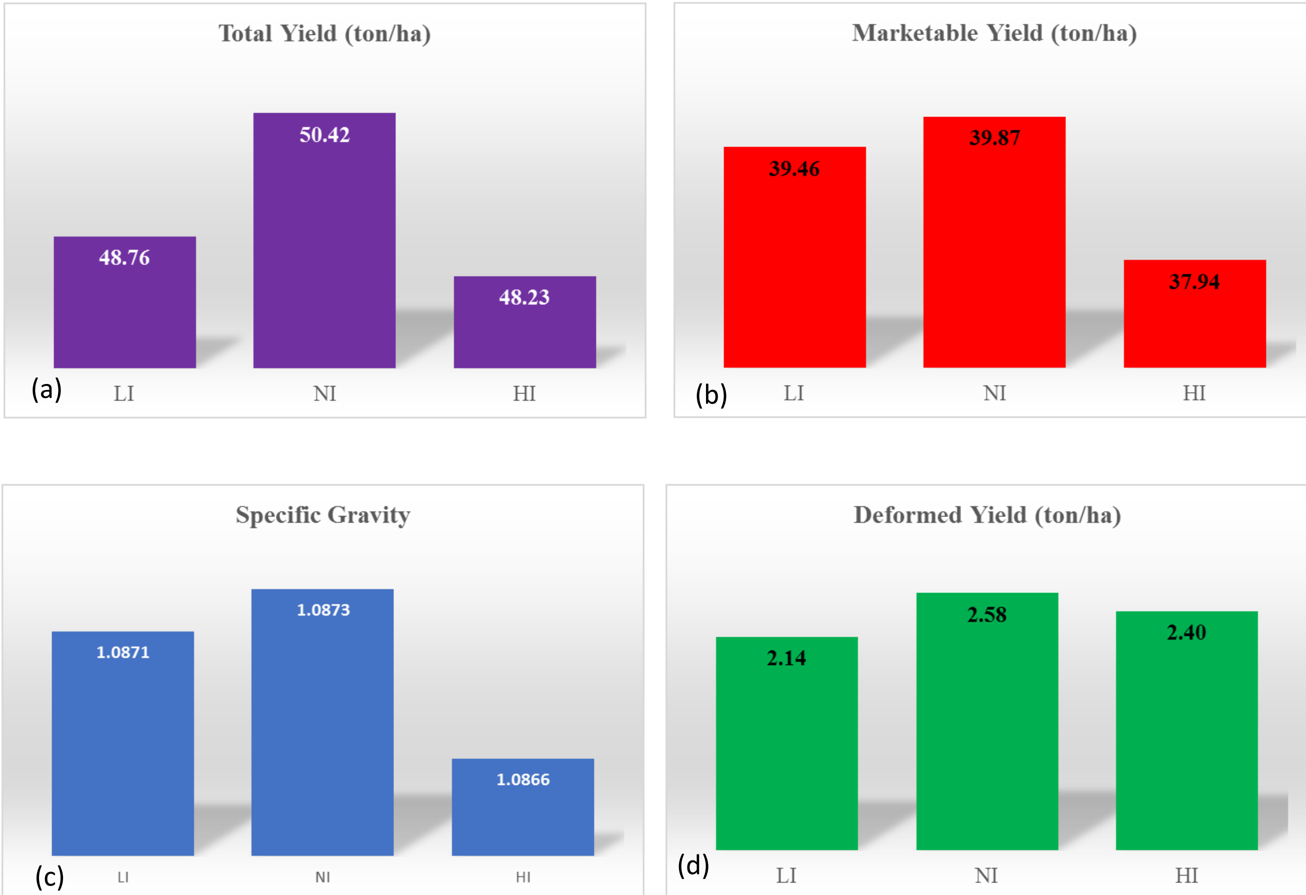


Figure 6.9 Mean total yield (a), marketable yield (b), specific gravity (c), and deform yield (d) for the three irrigation treatments in 2016, (HI: high irrigation, NI: normal irrigation, LI: low irrigation)

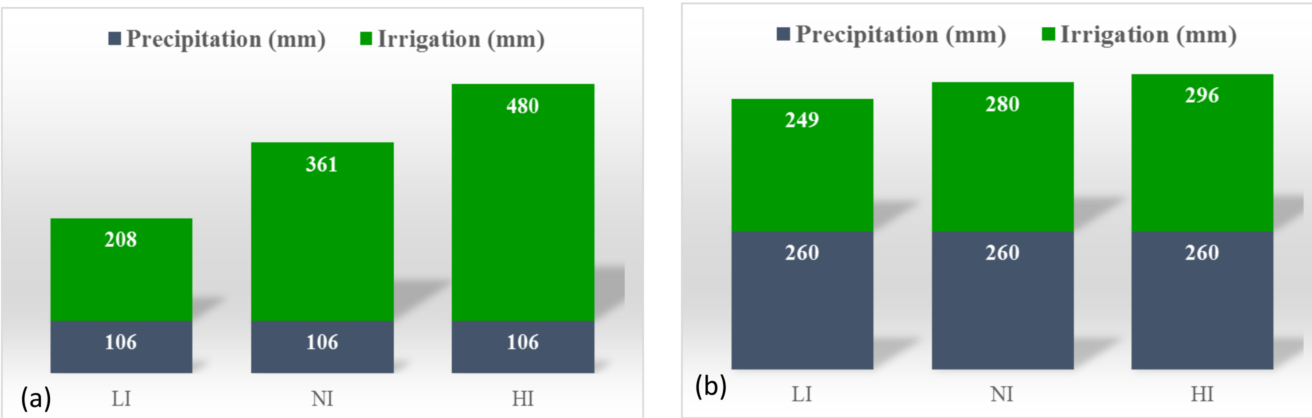


Figure 6.10 Mean irrigation and precipitation for the 2015 growing season (a), mean irrigation and precipitation for the 2016 growing season (b), (HI: high irrigation, NI: normal irrigation, LI: low irrigation)

Chapter 7

Summary and conclusions

7.1 General summary

Variable rate irrigation (VRI) is becoming increasingly in demand due to the limitations of conventional irrigation practices. Spatial and temporal variations are major factors that contribute to within-field crop-yield variation. The VRI is one of the most effective means to eliminate negative impacts of spatial and temporal variations and reduce within-field crop-yield variation. Variable-rate application can profoundly improve water and energy consumption, limit the movement of soil nutrients, decrease surface runoff, reduce non-uniformity of irrigation and fertilizer, improve crop quantity and quality, etc.

The overall goal of the research was to conserve water, optimise energy consumption, and improve crop yields under VRI in Lethbridge, southern Alberta. To this end, a four-year (2013-2016) field study was undertaken to address research objectives.

7.2 Conclusions

Objective 1:

Performance evaluation of constant versus variable rate irrigation

The performance of a five-span CPIS retrofitted with a VRI package was evaluated with different irrigation treatments during the 2013 and 2014 growing seasons under constant and variable application depths. In 2013, measurements for the catch-can trials happened to be taken at times with three different wind speeds. The measured water depths in the experimental plots were significantly influenced by wind speed. One of the more significant findings to emerge from the study was that wind speed greater than 3.3 m s^{-1} negatively affected application uniformity. The second major finding was that the application uniformity was not impacted with the variable application rates in the direction of center pivot travel. In the 2014 growing season, further catch-can tests along the pivot lateral revealed that the uniformity of application and accuracy of application were greatest with the 20.3 mm irrigation application depth with both the new and used sprinkler packages. Application uniformity was poor with 8.1 mm irrigation depth for the used sprinkler package. Overall system performance improved with the updating of the sprinkler package under both constant and variable-rate applications. The newer sprinkler package improved the mean application uniformity by 5.7% along the pivot lateral under constant and variable application depths. The mean application uniformity for the variable and constant application depths with new sprinkler package were 93.2% and 93.5%, respectively. It is necessary to be aware of the age, wear, and functionality of equipment, as it can impact the overall performance of an irrigation system. Evaluating and replacing worn nozzles is one of the least expensive cost in maintaining and improving CPIS performance.

Objective 2:

Assessment of field spatial and temporal variability to delineate site-specific management zones for variable-rate irrigation

The suitability of a stepwise multivariate regression approach in conjunction with a fuzzy C-mean clustering technique to create the optimum number of management zones based on the limited variables was assessed at the study site. The stepwise approach identified that the soil electrical conductivity (EC), pH, and field elevation were correlated with crop yield at this study site in southern Alberta. Since, salinity is one of the major problems in southern Alberta, it is more effective to delineate irrigation management zones based on the EC and field elevation for VRI.

Another important finding was that a fuzzy C-mean unsupervised clustering technique can be used to develop management zones using the EC and field elevation. The FPI and NCE validity criteria identified that three management zones were the optimum number of zones for the study site.

Statistical analysis showed that the delineated management zones were significantly different in terms of crop yields. The study area was categorized to low, medium, and high productive areas, which can be managed individually in terms of agricultural input application. The highest wheat grain yield (4.80 t ha^{-1}) was produced within high productive areas where the EC value was low (0.74 dS m^{-1}) and elevation was high (906 m). The lowest wheat grain yield (2.22 t ha^{-1}) was in low productive areas situated in the high EC (5.35 dS m^{-1}) and low elevation (903.5 m) areas.

Objective 3:

An assessment of water and energy consumption and crop productivity of variable-rate irrigation; A case study in southern Alberta, Canada

Water and energy consumption under variable and constant-rate applications were assessed during two growing seasons for a 27 ha field under a CPIS. The volumetric flow measurement at the pivot point of the system indicated that up to 34% less water can be applied with VRI versus non-VRI. Moreover, the average energy cost dropped by 18% with VRI during the 2013 and 2014 seasons. However, the water and energy consumption with a VRI strongly depends on site-specific prescription map. Static prescription maps for study site were generated at the beginning of two growing seasons based on the three management zones delineated with soil salinity and field topography.

The other major finding of this study was that higher water application in a low elevation and high EC areas resulted in no significant improvement on wheat grain yield, but by applying more irrigation in a high elevation and low EC area resulted in a high yield. The AquaCrop model was used to optimize crop productivity within the three management zones. Simulation of HRS wheat growth in the study area under the different irrigation scenarios indicated that the crop yield would be improved significantly with optimum irrigation application and drainage management.

Objective 4:

Application of variable-rate irrigation for potato productivity

The study investigated the potential crop productivity benefits of VRI technology under potato crop. In 2015, three irrigation applications were applied to Russet Burbank potatoes: normal irrigation (NI) representing 100% of recommended depth, low irrigation (LI) was 50% of recommended depth, and high irrigation (HI) was 150% of recommended depth. Higher water application in the experimental plots resulted in no significant improvement to potatoes yield. The harvest of tubers in NI plots proved to be more uniform in quality and size. The NI produced tubers of a larger size with lower specific gravity and higher glucose content. Furthermore, plots under NI had the lowest loss rate. Under-watered plots underperformed in every category, stressing the importance of water management under drought conditions. In addition, water and energy consumption under variable rate and non-variable rate applications were assessed during the 2015 growing season for a 27 ha field under a CPIS. Overall, 43% less water was applied, and a reduction of 12% in electricity cost was achieved.

In 2016, three irrigation applications were applied to Russet Burbank potatoes: normal irrigation (NI) representing 100% of recommended depth, low irrigation (LI) was 70% of recommended depth, and high irrigation (HI) was 130% of recommended depth. There were no significant differences among irrigation treatments for any of the yield and quality factors analyzed. This is likely because the differences in the amount of irrigation applied to the three treatments were very small due to precipitation over the growing season.

Chapter 8

8.1 Contributions to knowledge

The following are the contributions to knowledge from this research:

1. **Effective management zones delineation**

An important aspect of VRI is the delineation of irrigation management zones. This study presents a methodology to develop irrigation management zones with minimum available data. Effective management zones delineation depends upon an understanding of the spatial and temporal field variability. Ideally, the delineation of irrigation management zones will be very effective using large volumes of spatial and temporal data. However, obtaining large volumes of spatial and temporal data of soil properties and crop yield at relatively low cost is the biggest challenge of VRI. The methodology employed in this study proved that, the optimum and effective number of irrigation management zones can be delineated based on the limited variables such as soil salinity and field topography. On-the-go sensor technologies in combination with the global navigation satellite systems made it possible to provide an inexpensive data package that is crucial for management zones delineation. This ultimately allows further development of VRI strategy in terms of cost effectiveness of management zones delineation.

2. **Water and energy consumption of VRI technology**

This research project highlighted the significant reduction of water consumption and energy cost of VRI technology. Modifying the existing irrigation systems to VRI capability or the purchasing of new irrigation system integrated with VRI package can save up to 34% irrigation water, and reduction of 18% of energy cost. The reduction of water and energy consumption varies based on the field spatial and temporal variability. These findings would be significant incentives for adoption of VRI by stakeholder and irrigators and eventually lead the irrigation sector to utilize more efficient irrigation technologies.

3. **Application of decision support system and VRI management strategy for crop productivity**

The HRS wheat productivity under VRI technology during the 2013 to 2016 growing seasons was investigated. The AquaCrop model was used to optimize crop productivity within the three management zones. Simulation of HRS wheat growth in the study area under the different irrigation scenarios indicated that the crop yield would be improved significantly with optimum irrigation application and proper drainage management.

4. **Application of VRI for potato productivity**

In the 2015 and 2016 growing seasons, the effect of VRI strategy in potato crop was investigated in the study area. The findings of the study indicated that higher water application in the experimental plots resulted in no significant improvement to potatoes yield. The harvest of tubers in normal irrigation plots proved to be more uniform in quality and size. Over-irrigation not only did not increase potato yield, but also damaged tuber quality and wasted the irrigation water.

8.2 Recommendations for future research

1. **Further research in the field of VRI regarding the potential economic benefits would be of great help in adoption of site-specific management strategies.**

The potential economic benefits of VRI technology has not been investigated. From a farmer's perspective economic benefit is the most important incentive for adoption of this new technology. The knowledge gap on the economic benefits of VRI is a major detriment to adoption. Further research on the economic benefits of VRI needs to be done to clarify the full potential of this modern technology.

2. **Developing a simple decision support system to generate dynamic irrigation prescription maps is a vital tool to support development of VRI.**

Research so far has contributed to the performance evaluation and potential water and energy savings benefits of VRI technology. The current findings have provided some basic tools and knowledge to create static management zones and simple irrigation prescription maps. Considerably more research will need to be done to delineate dynamic irrigation prescription maps based on the immediate feedback from soil and crop conditions. Interactive web based decision support system can be developed to integrate continuous real-time soil water tensions/content with meteorological data and other related inputs to delineate a dynamic irrigation prescription maps.

3. Energy conservation

Improving energy efficiency in agricultural sectors can reduce greenhouse gas emissions. Most pump stations in irrigated fields operate inefficiently due to oversized-motor and variable demands. Recently, there has been growing interest to develop VRI strategy to conserve water and energy consumptions. Energy saving would be significant by use of variable-frequency drive (VFD) technology to meet variable demands. The VFD can provide energy saving by matching motor speed to the variable water demands. Therefore, energy conservation in agricultural sectors by means of new technologies would be one of the efficient way of reducing overall GHG emissions.

References

Adamchuk, V.I., Hummel, J.W., Morgan, M.T., Upadhyaya, S.K., 2004. On-the-go soil sensors for precision agriculture. Computers and Electronics in Agriculture, 44(1), 71-91.

AECOM Canada Ltd., 2009. Irrigation sector conservation, efficiency, and productivity planning report. Prepared for Alberta irrigation sector CEP plan steering committee. September 2009, 83 p. Available online: http://www.albertawatercouncil.ca/LinkClick.aspx?fileticket=9MN63bu_OV8%3D&tabid=115

Alberta Agriculture and Forestry, 2001. Agri-Facts: Practical information for Alberta's agriculture industry - Salt tolerance of plants, Government of Alberta. Available on-line: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex3303/$file/518-17.pdf?OpenElement

Alberta Agriculture and Forestry, 2004. Agri-Facts: Practical information for Alberta's agriculture industry, Alberta fertilizer guide, Government of Alberta. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex3894/$file/541-1.pdf?OpenElement

Alberta Agriculture and Forestry, 2008. Alberta irrigation energy calculator, Edmonton, Alberta, Canada. Available online: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr12448

Alberta Agriculture and Forestry, 2010. Alberta irrigation management model, Edmonton, Alberta, Canada. Available online: http://www.agric.gov.ab.ca/acis/imcin/aimm.jsp

Alberta Agriculture and Forestry, 2011. Agri-Facts: Practical information for Alberta's agriculture industry - Irrigation scheduling for potato in southern Alberta, Government of Alberta. Available on-line: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex13571/$file/258_561-1.pdf?OpenElement

Alberta Agriculture and Forestry, 2013. Alberta irrigation management manual, Irrigation management branch, irrigation and farm water division, Lethbridge, Alberta, Canada, pp. 56.

Alberta Agriculture and Forestry, 2014. Alberta irrigation information; facts and figures for the year 2013, 33 p.

Alberta Agriculture and Forestry, 2015a. Alberta weather and climate data. Available online: http://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp

Alberta Agriculture and Forestry, 2015b. Irrigation information, technology and innovation branch of Alberta Agriculture and Food. Lethbridge, Alberta. Available online: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr7197

Alberta Irrigation Projects Association, 2010. Irrigation sector, conservation, efficiency, productivity plan 2005-2015, 42 p. Available online: http://www.aipa.ca/wp-content/uploads/2013/11/AIPA-CEP-Final-Version-1.pdf

Alberta Water Council, 2007. Water conservation, efficiency and productivity: Principles, definitions, performance measures and environmental indicators final report, prepared by the water conservation, efficiency and productivity definitions project team. January 2007, 35 p. Available online: http://awchome.ca/LinkClick.aspx?fileticket=DNItZciPdw8%3D&tabid=59

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. FAO - Food and Agriculture Organization of the United Nations, Rome, Italy.

Al-Kufaishi, S., Blackmore, B., Sourell, H., 2006. The feasibility of using variable rate water application under a central pivot irrigation system. Irrigation and Drainage Systems, 20(2), 317-327.

Andarzian, B., Bannayan, M., Steduto, P., Mazraeh, H., Barati, M.E., Barati, M.A., Rahnama, A., 2011. Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. Agricultural Water Management, 100(1), 1-8.

Andrade, M.A., O'Shaughnessy, S.A. and Evett, S.R., 2015. ARSmartPivot v.1; Sensor-based management software for center pivot irrigation systems. In 2015 ASABE Annual International Meeting (P.1) . American Society of Agricultural and Biological Engineers. New Orleans, Louisiana, USA.

Araya, A., Habtu, S., Hadgu, K.M., Kebede, A., Dejene, T., 2010. Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (Hordeum vulgare). Agricultural Water Management, 97(11), 1838-1846.

ASABE, 2007. Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles, ASABE, St. Joseph, Missouri, USA, 8 p.

ASTM International, 2008., Standard test methods for determination of the soil water chararcteristic curve for desorption using a hanging column, pressure extractor, chilled mirror hygrometer, and/or centrifuge (D6836-02), (2008). ASTM International, West Conshohocken, Pennsylvania, USA.

Baker, D.E., Suhr, N.H., 1982. Atomic absorption and flame emission spectrometry. Methods of soil analysis. Part 2, chemical and microbiological properties, 13-27.

Bartlett, A.C., Andales, A.A., Arabi, M. Bauder, T.A., 2015. A smartphone app to extend use of a cloud-based irrigation scheduling tool. Computers and Electronics in Agriculture, 111, 127-130.

Bellvert, J., Marsal, J., Mata, M. Girona, J., 2012. Identifying irrigation zones across a 7.5-ha 'Pinot noir' vineyard based on the variability of vine water status and multispectral images. Irrigation Science, 30(6), 499-509.

Bennett, R.D., Harms, T.E., 2011. Crop yield and water requirement relationships for major irrigated crops in southern Alberta, Canadian Water Resources Journal, 36(2), 159-170.

Bezdek, J.C., 1981. Pattern recognition with fuzzy objective function algorithms. Plenum Press, New York, USA.

Boluwade, A., Madramootoo, C., Yari, A., 2016. Application of unsupervised clustering techniques for management zone delineation: Case study of variable rate irrigation in southern Alberta, Canada. Journal of Irrigation and Drainage Engineering, 142(1), 05015007.

Booker, J.D., Bordovsky, J., Lascano, R.J., Segarra, E., 2006. Variable rate irrigation on cotton lint yield and fiber quality. In Beltwide cotton conferences, San Antonio, Texas, USA, p. 1768.

Boydell, B. and McBratney, A.B., 2002. Identifying potential within-field management zones from cotton-yield estimates. Precision agriculture, 3(1), 9-23.

Cambouris, A.N., Nolin, M.C., Zebarth, B.J. and Laverdière, M.R., 2006. Soil management zones delineated by electrical conductivity to characterize spatial and temporal variations in potato yield and in soil properties. American journal of potato research, 83(5), 381-395.

Camp, C.R., Sadler, E.J., Evans, D.E., 1997. Water and nitrogen management using a site-specific center pivot. In ASAE conference, Minneapolis, Minnesota, USA.

Camp, C., Sadler, E., 1997a. Capabilities of a center pivot irrigation system for precision management of water and nutrients. In irrigation associations exposition and technical conference proceedings. Arlington, Virginia, USA, 235-242.

Camp, C., Sadler, E., 1997b. Site-specific water, nutrient and pesticide management. Irrigation Journal, 47, 14-16.

Camp, C., Sadler, E., Evans, D., Millen, J., 2001. Irrigation and nitrogen management with a site-specific center pivot. In ECPA: Proceedings of the 3rd European conference on precision agriculture, Montpellier, France.

Camp, C.R. Sadler, E.J., 1998. Irrigation site-specific crop management with a center pivot. Journal of Soil and Water Conservation, 53(4), 312-314.

Casanova, J.J., O'Shaughnessy, S.A., Evett, S.R. Rush, C.M., 2014. Development of a wireless computer vision instrument to detect biotic stress in wheat. Sensors, 14(9), 17753-17769.

Chávez, J.L., Pierce, F.J., Elliott, T.V., Evans, R.G., 2010a. A remote irrigation monitoring and control system for continuous move systems. Part A: Description and development. Precision Agriculture, 11(1), 1-10.

Chávez, J.L., Pierce, F.J., Elliott, T.V., Evans, R.G., Kim, Y., Iversen, W.M., 2010b. A remote irrigation monitoring and control system (RIMCS) for continuous move systems. Part B: Field testing and results. Precision Agriculture, 11(1), 11-26.

Christiansen, J.E., 1942. Irrigation by sprinkling. Agricultural Experiment Station. Bulletin No. 570. University of California, Berkeley, California, USA.

Charles, H., Chad, H., 2014. A demonstration of energy and water savings potential of variable rate irrigation. In 2014 ASABE and CSBE annual international meeting. Montreal, Quebec, Canada.

Corkal, D.R., Adkins, P.E., 2008. Canadian agriculture and water. In 13th International Water Resource Association, World Water Congress, Montpellier, France.

Corwin L. D., 2013. Site-specific management and delineating management zones. In. Precision agriculture for sustainability and environmental protection. (ed) M. Oliver. Routledge, 136-157.

Daccache, A., Knox, J.W., Weatherhead, E.K., Daneshkhah, A. Hess, T.M., 2015. Implementing precision irrigation in a humid climate; Recent experiences and on-going challenges. Agricultural Water Management, 147, 135-143.

Da Silva, J.M. Silva, L.L., 2008. Evaluation of the relationship between maize yield spatial and temporal variability and different topographic attributes. Biosystems Engineering, 101(2), 183-190.

Doorenbos, J., Kassam, A., 1979. Yield response to water. FAO irrigation and drainage paper (33).

Duke, H., Heermann, D., Fraisse, C. 1992. Linear move irrigation system for fertilizer management research. In proceedings international exposition and technical conference. Irrigation Association. Fairfax, Virginia, USA, 72-81.

Dukes, M.D., Perry, C., 2006. Uniformity testing of variable-rate center pivot irrigation control systems. Precision Agriculture, 7(3), 205-218.

Evett, S.R., Colaizzi, P.D., Schwartz, R.C. O'Shaughnessy, S.A., 2014. Soil water sensing; focus on variable rate irrigation. In proceedings of the 26th annual central plains irrigation conference, Burlington, Colorado, USA, 99-109.

Evans, R.G., LaRue, J., Stone, K.C. King, B.A., 2013. Adoption of site-specific variable rate sprinkler irrigation systems. Irrigation Science, 31(4), 871-887.

Evans, R.G., Sadler, E. J., 2013. Site-specific irrigation water management. In. Precision agriculture for sustainability and environmental protection. (ed) M. Oliver. Routledge, 172-190.

Fraisse, C.W., Sudduth, K.A. Kitchen, N.R., 2001. Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity. Transactions of the ASAE, 44(1), p.155.

Fraisse, C.W., Heermann, D.F. Duke, H.R., 1995. Simulation of variable water application with linear-move irrigation systems. Transactions of the ASAE, 38(5), 1371-1376.

Fraisse, C., Heermann, D., Duke, H., 1993. Modified linear move system for experimental water application. Advances in planning, design and management of irrigation systems as related to sustainable land use, Leuven, Belgium.

Fleming, K.L., Westfall, D.G., Wiens, D.W., Brodahl, M.C., 2000. Evaluating farmer defined management zone maps for variable rate fertilizer application. Precision Agriculture, 2(2), 201-215.

Fleming, K., Westfall, D., Heermann, D., 2004. Evaluating soil color with farmer input and apparent soil electrical conductivity for management zone delineation. Agronomy Journal, 96(6), 1581-1587.

Fridgen, J.J., Fraisse, C.W., Kitchen, N.R. Sudduth, K.A., 2000. Delineation and analysis of site-specific management zones. In proceedings of the 2nd international conference on geospatial information in agriculture and forestry. Vol(2), 402-411.

Fridgen, J.J., Kitchen, N.R., Sudduth, K.A., Drummond, S.T., Wiebold, W.J., Fraisse, C.W., 2004. Management zone analyst. Agronomy Journal, 96(1), 100-108.

Food and Agriculture Organization of the United Nations (FAO), 2016. Irrigation water use. Available online:
http://www.fao.org/nr/water/aquastat/water_use_agr/index.stm.

García-Vila, M., Fereres, E., 2012. Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. European Journal of Agronomy, 36(1), 21-31.

Gavioli, A., de Souza, E.G., Bazzi, C.L., Guedes, L.P.C., Schenatto, K., 2016. Optimization of management zone delineation by using spatial principal components. Computers and Electronics in Agriculture, 127, 302-310.

Goldin, A., 1987. Reassessing the use of loss-on-ignition for estimating organic matter content in noncalcareous soils. Communications in soil science and plant analysis, 18(10), 1111-1116.

Gossel, A., Thompson, A.L., Sudduth, K.A. and Henggeler, J.C., 2013. Performance evaluation of a center pivot variable rate irrigation system. In 2013 Kansas City, Missouri, USA, (p. 1). American Society of Agricultural and Biological Engineers.

Haghverdi, A., Leib, B.G., Washington-Allen, R.A., Ayers, P.D., Buschermohle, M.J., 2015. Perspectives on delineating management zones for variable rate irrigation. Computers and Electronics in Agriculture, 117, 154-167.

Haghverdi, A., Leib, B.G., Washington-Allen, R.A., Buschermohle, M.J., Ayers, P.D., 2016. Studying uniform and variable rate center pivot irrigation strategies with the aid of site-specific water production functions. Computers and Electronics in Agriculture, 123, 327-340.

Han, Y.J., Khalilian, A., Owino, T.O., Farahani, H.J., Moore, S., 2009. Development of Clemson variable-rate lateral irrigation system. Computers and Electronics in Agriculture, 68(1), 108-113.

Hedley, C.B., Yule, I.J., 2012. Farmer uptake of variable rate irrigation technologies in New Zealand. In 10th international conference on precision agriculture, Denver, Colorado, USA, 15-18.

Hedley, C.B. Yule, I.J., 2009. Soil water status mapping and two variable-rate irrigation scenarios. Precision Agriculture, 10(4), 342-355.

Hezarjaribi, A., 2008. Site-specifi irrigation: Improvement of application map and a dynamic steering of modified centre pivot irrigation system. PhD Dissertation, Federal agricultural research centre, institute of production engineering and building research, Braunschweig, Germany.

Hornung, A., Khosla, R., Reich, R., Inman, D., Westfall, D.G., 2006. Comparison of site-specific management zones. Agronomy Journal, 98(2), 407-415.

Janzen, H., 1993. Soluble salts. In soil sampling and methods of analysis. Lewis Publishers, Boca Raton, Florida, USA, 161-166.

Kachanoski, R.G., Wesenbeeck, I.V. and Gregorich, E.G., 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Canadian Journal of Soil Science, 68(4), 715-722.

Khosla, R., Fleming, K., Delgado, J.A., Shaver, T.M. and Westfall, D.G., 2002. Use of site-specific management zones to improve nitrogen management for precision agriculture. Journal of Soil and Water Conservation, 57(6), 513-518.

Khosla, R., Westfall, D.G., Reich, R.M., Mahal, J.S. and Gangloff, W.J., 2010. Spatial variation and site-specific management zones. In. Geostatistical applications for precision agriculture, Springer Netherlands, 195-219.

Kitchen, N.R., Drummond, S.T., Lund, E.D., Sudduth, K.A., Buchleiter, G.W., 2003. Soil electrical conductivity and topography related to yield for three contrasting soil–crop systems. Agronomy journal, 95(3), 483-495.

Kitchen, N.R., Sudduth, K.A., Myers, D.B., Drummond, S.T., Hong, S.Y., 2005. Delineating productivity zones on claypan soil fields using apparent soil electrical conductivity. Computers and Electronics in Agriculture, 46(1), 285-308.

King, B.A. and Stark, J.C., 1997. Potato irrigation management (No. 789). University of Idaho, Cooperative Extension System, College of Agriculture.

King, B.A., Wall, R.W., 1998. Supervisory control and data acquisition system for site-specific center pivot irrigation. Applied Engineering in Agriculture, 14(2), 135-144.

King, B.A. Kincaid, D.C., 2004. A variable flow rate sprinkler for site-specific irrigation management. Applied Engineering in Agriculture, 20(6), p.765.

King, B., Stark, J., Wall, R., 2005. Site-specific water and nitrogen management for potatoes with center pivot irrigation. In 26th Annual International Irrigation Show, Phoenix, Arizona, USA.

King, B.A., Stark, J.C., Wall, R.W., 2006. Comparison of site-specific and conventional uniform irrigation management on potatoes. Applied Engineering in Agriculture, 22(5), 677-688.

King, B.A., Wall, R.W., Karsky, T.F., 2009. Center-pivot irrigation system for independent site-specific management of water and chemical application. Applied Engineering in Agriculture, 25(2), 187-198.

LaRue, J.L., 2011. Variable rate irrigation 2010 field results. American Society of Agricultural and Biological Engineers annual international meeting, Louisville, Kentucky, USA, 5714-5723.

Li, Y., Shi, Z., Wu, C.F., Li, H.Y., Li, F., 2008. Determination of potential management zones from soil electrical conductivity, yield and crop data. Journal of Zhejiang University Science B, 9(1), 68-76.

Li, Y., Shi, Z., Li, F., Li, H.Y., 2007. Delineation of site-specific management zones using fuzzy clustering analysis in a coastal saline land. Computers and Electronics in Agriculture, 56(2), 174-186.

Longchamps, L., Khosla, R., Reich, R. and Gui, D.W., 2015. Spatial and temporal variability of soil water content in leveled fields. Soil Science Society of America Journal, 79(5), 1446-1454.

Lu, Y.C., Sadler, E.J., Camp, C.R., 2005. Economic feasibility study of variable irrigation of corn production in southwest coastal plain. Journal of Sustainable Agriculture, 26(3), 69-81.

Lulai, E.C. and Orr, P.H., 1979. Influence of potato specific gravity on yield and oil content of chips. American Potato Journal, 56(8), 379-390.

Mazza, G., Hung, J. and Dench, M.J., 1983. Processing/nutritional quality changes in potato tubers during growth and long term storage. Canadian Institute of Food Science and Technology Journal, 16(1), 39-44.

McCann, I.R., Stark, J.C., 1993. Method and apparatus for variable application of irrigation water and chemicals. U.S. Patent 5,246,164.

McCann, I.R., King, B.A., Stark, J.C., 1997. Variable rate water and chemical application for continuous-move sprinkler irrigation systems. Applied Engineering in Agriculture, 13(5), 609-615.

McCarthy, A.C., Hancock, N.H., Raine, S.R., 2010. VARIwise: A general-purpose adaptive control simulation framework for spatially and temporally varied irrigation at sub-field scale. Computers and Electronics in Agriculture,70(1), 117-128.

McClymont, L., Goodwin, I., Mazza, M., Baker, N., Lanyon, D., Zerihun, A., Chandra, S., Downey, M., 2012. Effect of site-specific irrigation management on grapevine yield and fruit quality attributes. Irrigation Science, 30(6), 461-470.

Miller, K.A., Lo, T.H., Luck, J.D., Heeren, D.M., 2014. Combining site specific data with geospatial analysis to identify variable rate irrigation opportunities in irrigated agricultural fields. In 2014 ASABE/CSBE annual meeting, Montreal, Quebec, Canada.

Molin, J.P., Castro, C.N.D., 2008. Establishing management zones using soil electrical conductivity and other soil properties by the fuzzy clustering technique. Scientia Agricola, 65(6), 567-573.

Odeh, I.O.A., Chittleborough, D.J., McBratney, A.B., 1992. Soil pattern recognition with fuzzy C-means: Application to classification and soil-landform interrelationships. Soil Science Society of America Journal, 56(2), 505-516.

Oliver, M., Bishop, T., Marchant, B., 2013. Site-specific irrigation water management, Precision agriculture for sustainability and environmental protection. Routledge, 2013, 172-190.

Omary, M., Camp, C.R., Sadler, E.J., 1997. Center pivot irrigation system modification to provide variable water application depths. Applied Engineering in Agriculture, 13(2), 235-239.

O'Shaughnessy, S., Evett, S., Colaizzi, P., Howell, T., 2011. Application uniformity of a commercial center pivot variable rate irrigation system. In international irrigation show, San Diego, California, USA, 13 p.

O'Shaughnessy, S.A., Urrego-Pereira, Y.F., Evett, S.R., Colaizzi, P.D., Howell, T.A., 2013. Assessing application uniformity of a variable rate irrigation system in a windy location. Applied Engineering in Agriculture, 29(4), 497-510.

O'Shaughnessy, S.A., Evett, S.R., Andrade, A., Workneh, F., Price, J.A., Rush, C.M., 2016. Site-specific variable-rate irrigation as a means to enhance water use efficiency. In emerging technologies for sustainable irrigation, ASABE / IA irrigation symposium, Long Beach, California, USA, 59(1), 239-249.

Pan, L., Adamchuk, V.I., Martin, D.L., Schroeder, M.A., Ferguson, R.B., 2013. Analysis of soil water availability by integrating spatial and temporal sensor-based data. Precision Agriculture, 14(4), 414-433.

Pelcat, Y., McConkey, B., Basnyat, P., Lafond, G.P., Moulin, A., 2004. In-field management zone delineation from remote sensing imagery. The key to sustainable management, Regina, Saskatchewan, Canada, 12 p.

Peralta, N.R.L., Costa, J., Balzarini, M. and Angelini, H., 2013. Delineation of management zones with measurements of soil apparent electrical conductivity in the southeastern pampas. Canadian Journal of Soil Science, 93(2), 205-218.

Perry, C., Pocknee, S., 2003. Development of a variable-rate pivot irrigation control system. In proceedings of the 2003 Georgia water resources conference, University of Georgia, Athens, Georgia, USA, 5 p.

Perry, C., Pocknee, S., Hansen, O., 2003. A variable rate pivot irrigation control system. In proceedings of the fourth European conference on precision agriculture. European Commission on Preservation and Access, 6 p.

Redulla, C.A., Davenport, J.R., Evans, R.G., Hattendorf, M.J., Alva, A.K. and Boydston, R.A., 2002. Relating potato yield and quality to field scale variability in soil characteristics. American journal of potato research, 79(5), 317-323.

Ross, L.R. and Porter, W.L., 1969. Objective measurements of French fried potato quality. Laboratory techniques for research use. American Potato Journal, 46(6), 192-200.

Sadler, E., Evans, R., Stone, K., Camp, C., 2005. Opportunities for conservation with precision irrigation. Journal of Soil and Water Conservation, 60(6), 371-378.

Sadler, E.J., Evans, R.G., Buchleiter, G.W., King, B.A., Camp, C.R., 2000. Design considerations for site specific irrigation. In national irrigation symposium. American Society of Agricultural Engineers, Phoenix, Arizona, USA, 304-315.

Sadler, E.J., Camp, C.R., Evans, D.E., Usrey, L.J., 1996. A site-specific center pivot irrigation system for highly-variable coastal plain soils. Precision Agriculture, 827-834.

Sheldrick, B. H., Wang, C., 1993. Particle-size distribution. Soil sampling and method of analysis. Boca Raton, Florida, USA, 499-511.

Shock, C.C. and Wang, F.X., 2011. Soil water tension, a powerful measurement for productivity and stewardship. HortScience, 46(2), 178-185.

Singh, A., Saha, S., Mondal, S., 2013. Modelling irrigated wheat production using the FAO AquaCrop model in west bengal, india, for sustainable agriculture. Irrigation and Drainage, 62(1), 50-56.

Smith, R., Baillie, J., McCarthy, A., Raine, S., Baillie, C., 2010. Review of precision irrigation technologies and their application. National Centre for Engineering in Agriculture, University of Southern Queensland, Toowoomba, Technical Report, NCEA Publication, 1003017(1).

Stark, J.C., Westermann, D.T. and Hopkins, B., 2004. Nutrient management guidelines for Russet Burbank potatoes. University of Idaho, College of Agricultural and Life Sciences.

Stone, K.C., Bauer, P.J., Busscher, W.J., Millen, J.A., Evans, D.E., Strickland, E.E., 2010. Variable-rate irrigation management for peanut in the eastern Coastal Plain. In 5th national decennial irrigation conference proceedings, American Society of Agricultural and Biological Engineers, Phoenix Convention Center, Phoenix, Arizona, USA, 582-588.

Stone, K.C., Bauer, P.J., Busscher, W.J., Millen, J.A., Evans, D.E., Strickland, E.E., 2015. Variable-rate irrigation management using an expert system in the eastern coastal plain. Irrigation Science, 33(3), 167-175.

Storey, R.M.J. Davies, H.V., 1992. Tuber quality. In: The potato crop, Springer Netherlands, 507-569.

Sui, R., Fisher, D.K., 2015. Field test of a center pivot irrigation system. Applied Engineering in Agriculture, 31(1), 83-88.

Xiang, L.I., Yu-chun, P.A.N., Zhong-qiang, G.E. and Chun-jiang, Z.H.A.O., 2007. Delineation and scale effect of precision agriculture management zones using yield monitor data over four years. Agricultural Sciences in China, 6(2), 180-188.

Xin-Zhong, W., Guo-Shun, L., Hong-Chao, H., Zhen-Hai, W., Qing-Hua, L., Xu-Feng, L., Wei-Hong, H., Yan-Tao, L., 2009. Determination of management zones for a tobacco field based on soil fertility. Computers and Electronics in Agriculture, 65(2), 168-175.

Zebarth, B.J., Leclerc, Y., Moreau, G. and Botha, E., 2004. Rate and timing of nitrogen fertilization of Russet Burbank potato: Yield and processing quality. Canadian journal of plant science, 84(3), 855-863.

Zhang, X., Shi, L., Jia, X., Seielstad, G., Helgason, C., 2010. Zone mapping application for precision farming: A decision support tool for variable rate application. Precision Agriculture, 11(2), 103-114.

Valmont Industries, Inc., 2013. Variable rate irrigation zone option (Installation Manual), 88 pp.

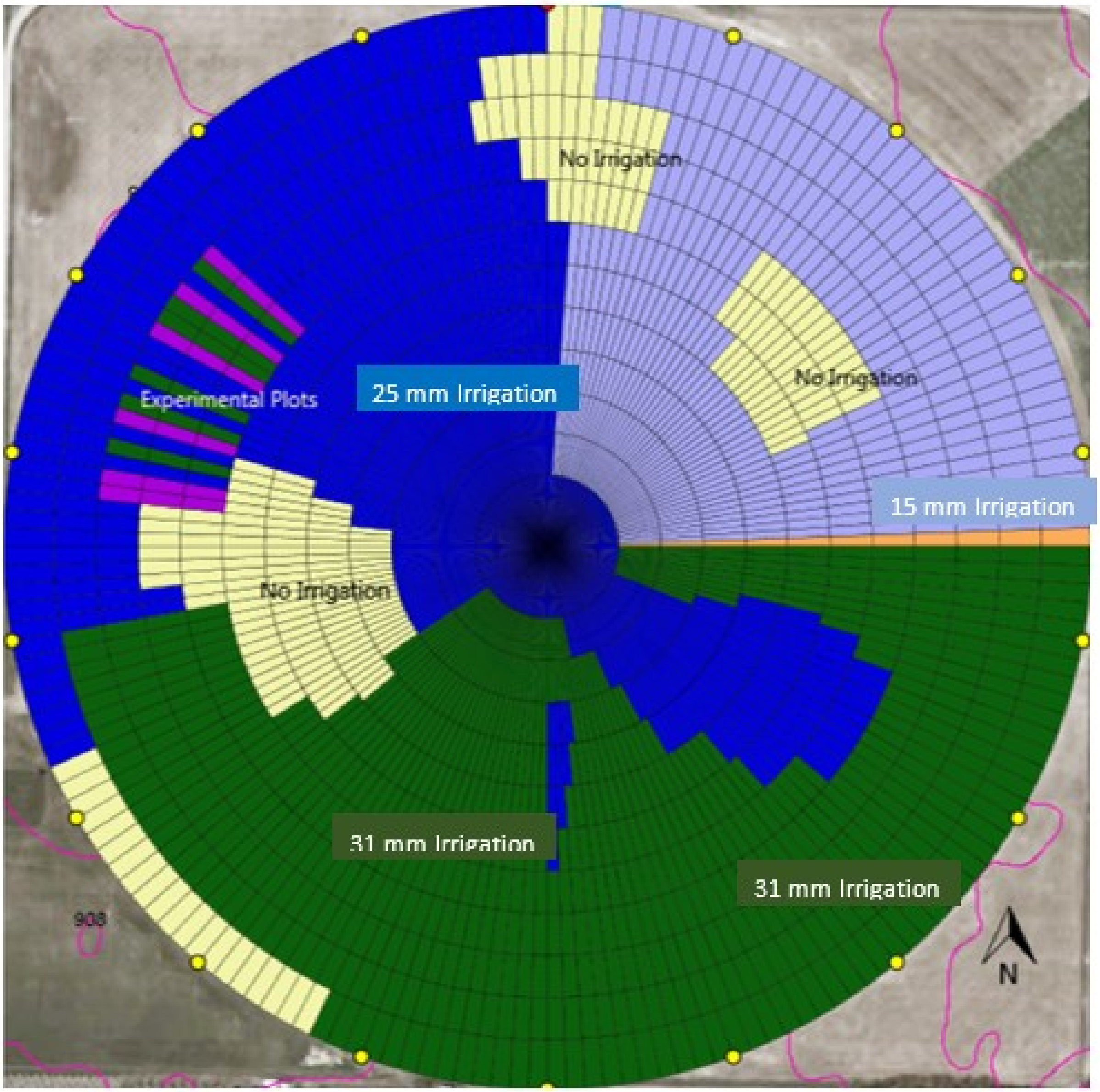
Wallender, W.W., Tanji, K.K., 2011. Agricultural salinity assessment and management (No. Ed. 2). American Society of Civil Engineers (ASCE).

Wood J., 2013. Cropping alternatives methodology, Government of Alberta. Available on-line: http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/ba3468a2a8681f69872569d60073fde1/638717e2d506efc787257e2a006f381f/$FILE/2013%20Cropping%20Alternatives.pdf

UN World Water Development Report (UNWWDR), 2014. Water and energy. Available on-line: http://unesdoc.unesco.org/images/0022/002257/225741E.pdf

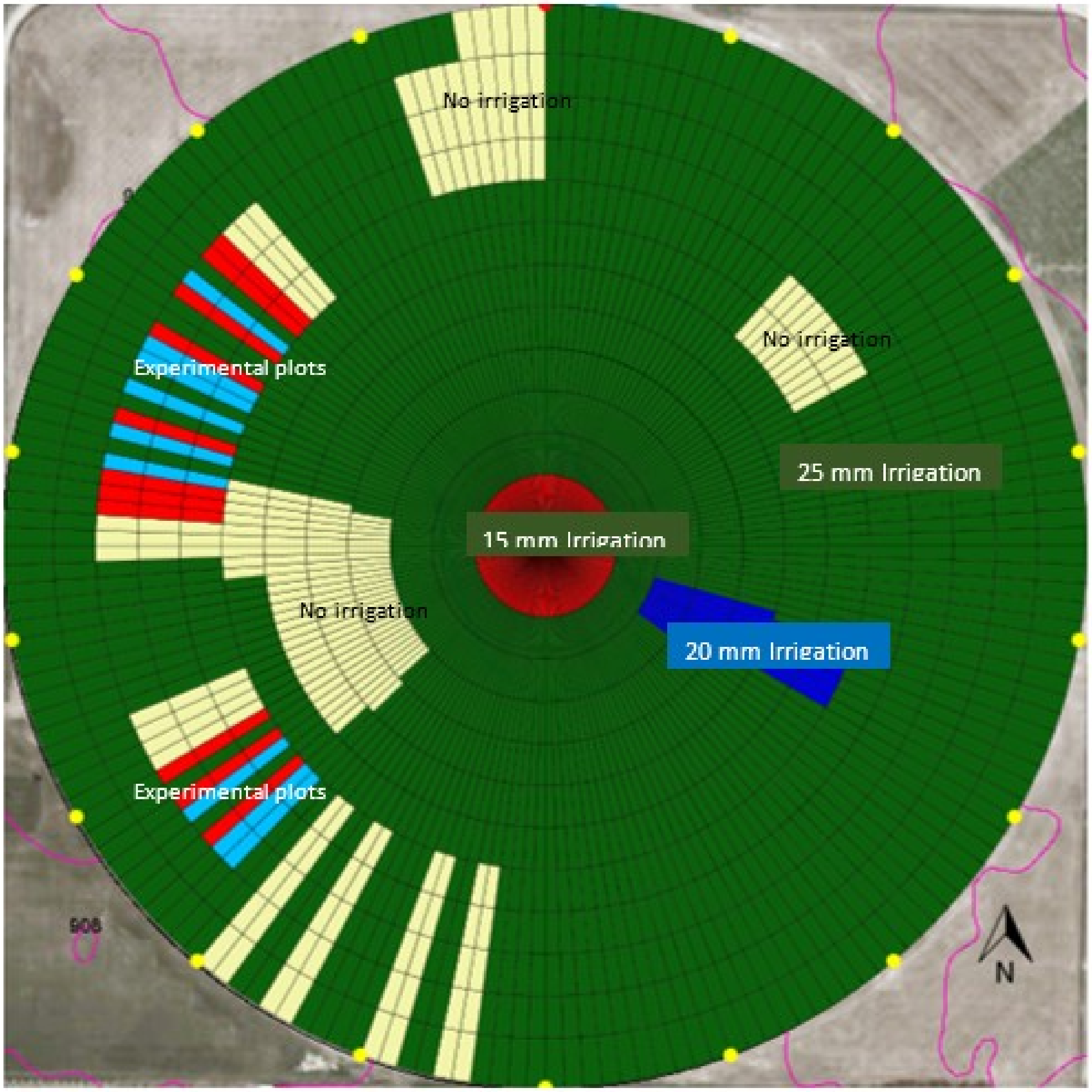
Appendices

A. Irrigation prescription map (2013)



Irrigation prescription map for the 2013 growing season produced by Variable Rate Prescription Software (version 6.5, Valmont Industries Inc., Omaha, Nebraska, USA)

B. Irrigation prescription map (2014)



Irrigation prescription map for the 2014 growing season produced by Variable Rate Prescription Software (version 6.5, Valmont Industries Inc., Omaha, Nebraska, USA)